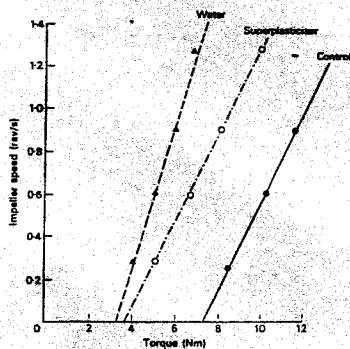
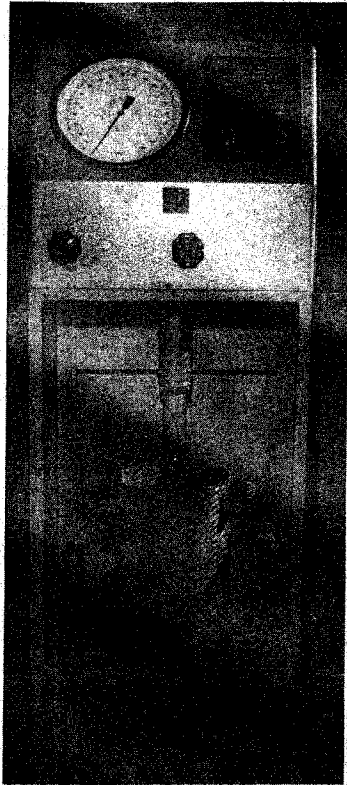




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REPAIR, EVALUATION, MAINTENANCE, AND REHABILITATION RESEARCH PROGRAM

TECHNICAL REPORT REMR-CS-18

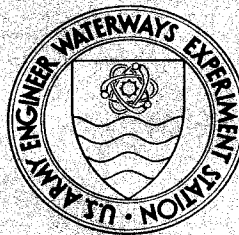
EVALUATION OF CONCRETE MIXTURES FOR USE IN UNDERWATER REPAIRS

by

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April 1988

Final Report

Approved For Public Release; Distribution Unlimited

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Under Civil Works Research Work Unit 32305

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188 Exp. Date: Jun 30, 1986	
1a. REPORT SECURITY CLASSIFICATION Unclassified			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution unlimited.		
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) Technical Report REMR-CS-18			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION USAEWES Structures Laboratory		6b. OFFICE SYMBOL (If applicable) CEWES-SC	7a. NAME OF MONITORING ORGANIZATION		
6c. ADDRESS (City, State, and ZIP Code) PO Box 631 Vicksburg, MS 39180-0631			7b. ADDRESS (City, State, and ZIP Code)		
8a. NAME OF FUNDING / SPONSORING ORGANIZATION US Army Corps of Engineers		8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER		
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20314-1000			10. SOURCE OF FUNDING NUMBERS		
			PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.
					WORK UNIT ACCESSION NO. 32305
11. TITLE (Include Security Classification) Evaluation of Concrete Mixtures for Use in Underwater Repairs					
12. PERSONAL AUTHOR(S) Neeley, Billy D.					
13a. TYPE OF REPORT Final report		13b. TIME COVERED FROM _____ TO _____		14. DATE OF REPORT (Year, Month, Day) April 1988	
				15. PAGE COUNT 130	
16. SUPPLEMENTARY NOTATION A report of the Concrete and Steel Structures problem area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP			
			Abrasion-erosion resistance High-range water reducers		
			Antiwashout admixtures Underwater placement of		
			Concrete mixtures concrete		
19. ABSTRACT (Continue on reverse if necessary and identify by block number)					
<p>Concrete mixtures were evaluated to determine which were most suited for placement underwater in thin lifts. The concretes were proportioned to have good workability, good abrasion-erosion resistance, and good resistance to washing out of the cement paste. High-range water reducers (HRWR) were used to increase the workability and permit the use of low water-cement ratios (W/C) to increase the resistance to abrasion-erosion. Low W/C, silica fume, and antiwashout admixtures (AWA) were used to increase the resistance to washout.</p> <p>A washout test was used to determine the relative amount of cement paste lost when the concrete is exposed to a large volume of water. The two-point workability test was used to evaluate the relative workability properties of each mixture. The slump and air content were also measured for most of the mixtures. The test method for abrasion-erosion resistance of concrete (underwater method) was used to determine the abrasion-erosion resistance of each mixture.</p> <p style="text-align: right;">(Continued)</p>					
20. DISTRIBUTION / AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a. NAME OF RESPONSIBLE INDIVIDUAL			22b. TELEPHONE (Include Area Code)		22c. OFFICE SYMBOL

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

19. ABSTRACT (Continued).

The results of these tests were used to determine the combination of materials necessary to produce concrete with the desired properties. Significant correlations that exist between the two-point measurements and washout measurements were examined. The effects that W/C, HRWR's, AWA's, fly ash, and silica fume have upon washout resistance and abrasion-erosion resistance were examined.

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PREFACE

The work described in this report was performed at the Structures Laboratory (SL), US Army Engineer Waterways Experiment Station (WES), under authority of Headquarters, US Army Corps of Engineers (HQUSACE), as a part of Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Work Unit No. 32305, "Techniques for Underwater Concrete Repairs."

The REMR Overview Committee of HQUSACE consists of Mr. James E. Crews and Dr. Tony Liu. Dr. Liu was also Technical Monitor. Program Manager for REMR was Mr. William F. McCleese, and the Problem Area Leader was Mr. James E. McDonald. The investigation was performed under the general supervision of Messrs. Bryant Mather, Chief, SL, and John M. Scanlon, Chief, Concrete Technology Division (CTD), SL. Direct supervision was provided by Mr. Kenneth L. Saucier, Chief, Concrete and Evaluation Group, CTD. Mr. Saucier was the Principal Investigator. Constructive guidance and criticism were also provided by Dr. Graham H. Rowe, Head, Concrete Section, Ministry of Works and Development, New Zealand, and Dr. W. L. Dolch, Civil Engineering Department, Purdue University. The laboratory work was directed by Mr. Billy D. Neeley, CTD, with assistance from Messrs. Mike Lloyd, Tom Lee, Julies Mason, Percy Collins, Frank Dorsey, Greg Comes, Toy Poole, and Ms. Carolyn Corbett. Mr. Neeley prepared this report. Permission to reproduce copyrighted materials from Fox and McDonald (1978) (Figure 1) and Tattersall and Banfill (1983) (Figures 2 through 7, B2, and B3) was granted by Wiley and Sons, Inc., and The Longman Group UK Ltd, respectively. The report was edited by Mrs. Gilda Miller with text and figure layout coordinated by Mrs. Chris Habeeb, Information Product Division, Information Technology Laboratory (WES).

COL Dwayne G. Lee, CE, is Commander and Director of WES. Dr. Robert W. Whalin is Technical Director.

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CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
cubic feet	0.02831685	cubic metres
cubic yards	0.07645549	cubic metres
feet	0.3048	metres
fluid ounces	0.00002957353	cubic metres
fluid ounces per cubic yard	0.038680715	litres per cubic metre
inches	25.4	millimetres
foot pounds (force)	1.355818	newton metres
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (mass) per cubic yard	0.5932764	kilograms per cubic metre

EVALUATION OF CONCRETE MIXTURES FOR USE IN UNDERWATER REPAIRS

PART I: INTRODUCTION

Background

1. In 1975, a study by the US Committee on Large Dams (USCOLD 1975) indicated that of 4,974 dams higher than 45 ft*, there had been 349 incidents of unsatisfactory or unsafe performance. The second highest cause of problems involving dams constructed after 1930 was erosion of the concrete in outlet works. A survey of Corps of Engineers Division and District offices in 1977 (OCE 1977) indicated erosion damage to the concrete in 52 structures. Although the majority of erosion damage has been in stilling basins, other areas such as channels, conduits, and lock emptying and filling laterals are also susceptible to this type of damage. Stilling basins are particularly susceptible to erosion because of the high velocities and turbulence of water plus the debris that it carries. The 1977 survey indicated depths of erosion ranging from a few inches to approximately 10 ft.

2. Many of the structures identified in the survey have been repaired in recent years. Unfortunately, the technology of repair materials that would be resistant to erosion damage was limited during the period that the repairs were being made. As a result, many of the repairs have been unsuccessful. Liu (1980) developed an abrasion-erosion test that revealed that some concretes are significantly more resistant to erosion than others. High-strength concrete made with silica fume and polymer-impregnated concrete have shown higher erosion resistance than conventional concretes.

3. In the past, most repairs made to stilling basins required dewatering of the basin. In many cases, this process accounted for over 40 percent of the total repair cost (McDonald 1980). The Corps is looking for possible techniques to make such repairs without dewatering the structure. Concrete has been placed underwater successfully, but usually has been in massive applications where high strengths were not required. Gerwick et al. (1981) conducted research in this area, and guidance is available in this report.

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 8.

Repairing erosion damage to a stilling basin without dewatering could require placing concrete in relatively thin lifts. There are no current guidelines concerning proper equipment and procedures for placing concrete underwater in thin lifts, or for concrete mixtures that have improved abrasion-erosion resistance and are suitable for placement underwater in thin lifts.

4. Since the technology identifying the placement technique most suitable for making the repairs described above is not available, it is difficult to predict how resistant the concrete must be to washout for any given placement technique. A concrete that has good abrasion-erosion resistance when mixed may not have this property when placed underwater if a large quantity of the cement paste washes out on contact with the water. WES has conducted a study within the ongoing Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program to evaluate the amount of washout to be expected in typical concrete mixtures that have good abrasion-erosion resistance. Proprietary products that claim to reduce the susceptibility of concrete to washout were evaluated. The Two-Point Workability Apparatus (Tattersall 1976) was used to evaluate the workability characteristics of all mixtures.

Literature Review

Methods of placement

5. For many years concrete has been successfully placed underwater using the tremie method. A tremie is a pipe long enough to reach from above water to the location underwater where the concrete is to be deposited. Usually, a hopper is attached to the top of the pipe to receive the concrete, and the lower end is capped to prevent water from entering the pipe while it is being lowered into the water. Once the tremie is filled with concrete, it is raised slightly, allowing the end cap to break. The concrete then flows out of the tremie embedding the lower end of the pipe in a mound of the concrete. All subsequent concrete flows into the mound and is never exposed directly to the water since the mouth of the tremie must be kept embedded in the fresh concrete at all times. If this embedment is not maintained, water will enter the tremie. Any subsequent concrete flowing down the tremie will fall through the water resulting in the washing out of cement and segregation of aggregates. However, with the use of an antiwashout admixture, it may not be as critical for the mouth of the tremie pipe to remain buried in the concrete.

6. In recent years other methods for placing concrete underwater have been developed. For many applications in Europe and Japan, pumped concrete has become preferred over the traditional tremie pipe. There are fewer transfer points for the concrete, the problems associated with gravity feed are eliminated, and the use of a boom permits better control during placement.

7. The hydrovalve method (Schoewert and Hillen 1972) and Kajima's Double Tube Tremie (KDT) method (Nakahara, Ohtomo, and Yokota 1976) are variations of the traditional tremie method. The hydrovalve method uses a flexible hose that collapses under hydrostatic pressure and thus carries a controlled amount of concrete down the hose in slugs. This slow and contained movement of the concrete helps to prevent segregation. An advantage of this method is that stiffer concretes with slumps less than 5-1/2 in. can be placed, as can the higher workability mixtures used with the traditional tremie. The KDT method varies in that the flexible hose is encased inside a steel pipe. The mouth of the steel pipe can be buried in the concrete, as with the traditional tremie method.

8. The Abetong-Sabema (Remmer and Henriksen 1982) and the Shimizu (Shimizu) pneumatic valves are attached to the end of a concrete pump line mounted on a pumping boom. The valves permit better control of the flow of concrete through the lines and even termination of the flow to protect the concrete within the lines while the boom is being moved. The Shimizu pneumatic valve incorporates a level detector with the valve unit. Good results have been obtained using pneumatic valves to place concrete underwater.

9. An unusual approach has been taken by the Sibo group in Osnabruck, Germany (Gerwick, in preparation). A special barge has been constructed with tilting pallets along the deck. Concrete is spread in a uniform layer on the tilting pallets and then dropped into the water in a free-fall. An antiwash-out admixture is required. This method allows for the placement of thin, uniform layers of concrete in shallow water, and could perhaps be adapted for use in deeper water.

10. Concrete can be placed underwater by lowering a bucket or bottom-dumping skip through the water and then discharging the concrete. Stiff, dense concrete could be placed with this method if used in combination with a method of underwater consolidation. An antiwashout admixture (AWA) should be used. More details on the current technology for making underwater repairs are given by Gerwick (in preparation).

11. These different methods of concrete placement underwater have been mentioned to illustrate the variety of conditions to which the concrete could be exposed while being placed. Some methods such as the tremie and the pump are designed to protect the concrete from exposure to the water; others, such as the Sibo tilting pallet barge, rely on AWA's to protect the concrete.

Antiwashout admixture

12. Ramachandran (1984) classified AWA's, or pump-aids, into five categories:

- a. Class A. Water-soluble synthetic and natural organic polymers, which increase the viscosity of the mixing water. Examples include cellulose ethers, pregelatinized starches, polyethylene oxides, alignates, carrageenans, polyacrylamides, carboxyvinyl polymers, and polyvinyl alcohol. The dosage range used is 0.2 to 0.5 percent solid by mass of cement.
- b. Class B. Organic water-soluble flocculants, which are absorbed on the cement particles and increase viscosity by promoting interparticle attraction. Examples include styrene copolymers with carboxyl groups, synthetic polyelectrolytes, and natural gums. The dosage range used is 0.01 to 0.10 percent solid by mass of cement.
- c. Class C. Emulsions of various organic materials, which increase interparticle attraction and also supply additional superfine particles in the cement paste. Examples include paraffin-wax emulsions that are unstable in the aqueous cement phase, acrylic emulsions, and aqueous clay dispersions. The dosage range used is 0.10 to 1.50 percent solid by mass of cement.
- d. Class D. Inorganic materials of high surface area, which increase the water-retaining capacity of the mix. Examples include bentonites, pyrogenic silicas, silica fume, milled asbestos, and other fibrous materials. The dosage range used is 1 to 25 percent solid by mass of cement.
- e. Class E. Inorganic materials that supply additional fine particles to the mortar pastes. Examples include fly ash, hydrated lime, kaolin, diatomaceous earth, other raw or calcined pozzolanic materials, and various rock dusts. The dosage range used is 1 to 25 percent solid by mass of cement.

13. Class D and E materials used in excess of two percent are only those which have an inherent pozzolanic or hydraulic activity. The addition is usually made as a cement replacement.

14. Liquid materials can be added with the water, and fine powders can be blended with the sand. Some materials such as polyethylene oxides, cellulose ethers, and some polyelectrolytes are hygroscopic and tend to form

clumps that are slow to dissolve. To ensure uniform distribution, these materials should be dissolved gradually in water prior to mixing.

15. Some materials may produce an initial stiff consistency; however, additional mixing allows the polymers to dissolve gradually, thus producing a wetter consistency. The admixtures generally enhance the workability when used in lean and harsh mixtures but may have an opposite effect upon mixtures with higher cement contents due to a much increased water demand. Class A, B, and C materials act by increasing the viscosity of the cement paste, while class D and E materials influence the void structure by filling pores. Cellulose ethers, starches, and polyethylene oxide are potent retarders that may delay setting times, especially in mixtures with high water-cement ratios. Class A, B, and C materials have surfactant properties that lower the surface tension of the aqueous phase of the mixture. Therefore, depending on other mixture proportions, dosages above optimum levels may entrain excessive air contents. If water-cement ratios are held constant, a slight strength reduction will generally be noticed, particularly at early ages. The extent of the strength reduction depends upon the admixture dosage, air content, consistency, and degree of retardation of time of setting.

16. Maage and Hjollo (1983) examined six different concrete mixtures with antiwashout admixtures by letting the concrete free-fall through 55 cm of water. The concrete was allowed to flow into place, and no additional consolidation was applied. A concrete without an AWA traditionally good for underwater placement was used as a control. All mixtures were proportioned for a high degree of workability. No attempt was made to get the same compressive strength in the seven mixtures.

17. The results indicated that the concretes with an AWA sustained the fall through water without a serious reduction in compressive strength when compared to the same concrete cast-in-air. Four of the mixtures with an antiwashout admixture retained over 80 percent of the cast-in-air strength, while the traditionally good concrete retained only 18 percent of its cast-in-air strength. Five of the mixtures with an AWA filled in around the reinforcing steel and other obstacles better than the control. Four of the mixtures with an AWA had less than 5 mm of weak mortar settled on top of the concrete, while the control had up to 40 mm of washed-out fines. From a rheological standpoint, the mixtures with an AWA were very mobile even though they were tough and sticky.

18. The manufacturer of the proprietary AWA "Rescon-T" examined the effect of the admixture on several different concretes (Rescon A/S, 1983). The concrete was placed underwater by lowering a bottom dump bucket to approximately 1 m above the form and allowing the concrete to fall into the form. The concrete was self-leveling and required no external consolidation. Approximately 2 mm of weak mortar settled on top of the concrete after casting. Later examination revealed virtually no voids in the slab, even around reinforcing steel.

19. A second series of tests by the manufacturer examined the effect of different amounts of Rescon-T in five mixtures with different water-cement ratios and different amounts of Rescon-T in five mixtures containing silica fume and different water-cement ratios. Cubes were cast in air for controls, and underwater by allowing the concrete to fall through approximately 1 m of water. The results indicated that the mixtures with silica fume retained from 53 to 87 percent of their cast-in-air strength, while the mixtures without silica fume retained 20 to 80 percent of their cast-in-air strength. The percentage of cast-in-air strength that was retained increased as the dosage of Rescon-T increased. These results indicate that AWA's, if used in properly proportioned mixtures and in proper quantities, do reduce the amount of cement that is washed out of the concrete when permitted to drop through water.

20. Makk, Tjugum, and Westergren (1986) placed three mixtures underwater using the Abetong-Sabema pneumatic valve method. The first mixture was a traditional concrete, the second contained Rescon-T, and the third contained silica fume and Rescon-T. Both mixtures containing Rescon-T were more mobile than the control and provided good embedment of the reinforcing steel. Weak mortar was collected to a depth of 50 to 80 mm on top of the control specimen, but less than 25 mm on the mixtures containing Rescon-T. Also, some of the reinforcing steel in the control specimen was coated with weak mortar, while the weak mortar formation was minimal on the reinforcing steel in the specimens with Rescon-T.

21. With the exception of one mixture, all of the concretes mentioned above had water-cement ratios above 0.50. Liu (1980) showed that lower water-cement ratios are required to provide improved abrasion-erosion resistance.

Workability

22. Powers (1932) defined workability as "that property of a plastic concrete mixture which determines the ease with which it can be placed, and

the degree to which it resists segregation. It embodies the combined effect of mobility and cohesiveness." While this definition is simple and straightforward, the property itself is complex and difficult to measure.

23. Tattersall (1976) lists five factors that affect the workability of concrete:

- a. Time. The workability of a mixture decreases as time elapses after mixing. The loss of workability is greater in the first few minutes after mixing.
- b. Aggregate properties. The particle shape, particle size distribution, porosity, and surface texture influence the workability of a mixture. With a given cement and water content, a mixture with a smooth, rounded, large aggregate with a low porosity is more workable than a mixture with a rough, angular, small aggregate with a high porosity.
- c. Cement properties. The influence of cement properties upon workability is more important in mixtures with a high cement content. A cement with a high fineness will cause a concrete mixture to lose workability more rapidly than will an ordinary portland cement because of its rapid hydration.
- d. Admixtures. Most admixtures affect the workability of a mixture even though their main purpose lies elsewhere. On the other hand, the main objective of water-reducing admixtures is to increase workability while holding water and cement contents constant, or hold workability constant while decreasing water and cement contents. High range water-reducing admixtures (HRWR), or superplastizers, are so effective that flowing and self-leveling concrete can be produced.
- e. Mixture proportions. The relative proportions of all constituents affect the workability of the mixture. Powers (1932) and many others have also presented theories of the factors affecting the workability of concrete. The attempts to measure workability have been as varied and controversial as the theories of the factors affecting the workability. Many test methods have been proposed, yet few have gained acceptance and widespread use. All have been criticized because they are empirical and do not really measure workability. Tattersall (1976) lists 10 tests and discusses the merits and shortcomings of each. A few of these methods have gained enough acceptance to become standardized in the USA or the United Kingdom, for example the slump, flow, and compacting factor tests. However, Gerwick et al. (1981) state, "There is no single test which will provide definitive data on the workability of a concrete mixture."

24. Some researchers have taken a rheological approach in an attempt to measure workability. If a liquid is confined between two parallel planes, as shown in Figure 1, with one plane moving at a constant velocity due to a constant applied force, the constant of proportionality between the strain

rate and the shear stress, τ , is defined as the absolute viscosity, η , where dv/dy is the velocity gradient, or the rate of shear, γ .

$$\tau = \eta \frac{dv}{dy}$$

A liquid that obeys this law is called Newtonian. The relationship between shear rate and shear stress is shown graphically in Figure 2.

25. Many materials have a minimum stress, or yield value, below which no flow occurs. Materials of this type follow the equation

$$\tau = \tau_0 + \mu\gamma$$

where τ_0 is the yield value and μ is the plastic viscosity. This model is called a Bingham body, and its behavior is shown graphically in Figure 3.

26. Tattersall (1971), Uzomaka (1974), Murata and Kikukawa (1973), Morinaga (1973), Saluta, et al. (1979), L'Hermite (1951), Ritchie (1967), and Komlos (1966) have reported attempts to apply this theory to measuring the properties of freshly mixed concrete using a coaxial cylinder viscometer. Many problems were encountered, and the results were widely scattered and generally unsuccessful. The criticisms cast serious doubt upon the validity of the results.

27. Tattersall and Banfill (1983) attempted to overcome some of the problems of the coaxial cylinder viscometer by using a Hobart food mixer fitted with a hook to stir the concrete. A value for torque, in arbitrary units, was obtained by dividing the power required to run the mixer by the speed of the mixer. Torque, T , was then plotted against speed, N , and a linear relationship was discovered. The curves could be represented by the equation

$$T = g + hN$$

where g is the intercept on the torque axis and h is the reciprocal of the slope of the line. Since this is the form of the equation for the Bingham model, it is implied that g is a measure of the yield value, τ_0 , and h is a measure of the plastic viscosity, μ . Tattersall contends that the workability of concrete can be measured by these two parameters. Rixom (1978) states that the g value should be related to the cohesion of the concrete, while the h value is related to the workability. Tattersall and Bloomer (1979) and Bloomer (1979) give mathematical and theoretical justification for g and h being measures of τ_0 and μ , respectively.

28. Later models of the machine used as an infinitely variable hydraulic transmission and a 4.75:1 worm-and-pinion right-angled reduction gear. A

value for torque was obtained by measuring the oil pressure developed in the hydraulic unit. Experiments have confirmed that the torque is proportional to the pressure developed in the unit.

29. The two-point test will measure differences in concrete that are not detected by the slump test. Figures 4, 5, and 6 illustrate the effects of water, HRWR, aggregate type, and fines content on mixtures having the same slump. Figure 7 illustrates the effect of time on mixtures containing HRWR.

Objectives of This Study

30. The objectives of this work were to develop concrete mixtures suitable for placement underwater that are resistant to washout and that have a high resistance to abrasion-erosion. A washout test, described in detail in Appendix A, was used to determine the relative amount of cement paste lost when the concrete is dropped through water. The two-point workability apparatus was used to evaluate the relative workability properties of each mixture. The two-point workability test method is described in Appendix B. The slump and air content were also measured for most of the mixtures. The test method for abrasion-erosion resistance of concrete (underwater method), CRD-C 63-80, Handbook for Concrete and Cement (US Army Engineer Waterways Experiment Station 1949) was used to determine the abrasion-erosion resistance of each mixture.

31. The results of these tests were used to determine the combination of materials necessary to produce concrete with the desired properties. Any significant correlations that exist between the two-point measurements and washout measurements were examined. The effect of AWA upon strength and abrasion-erosion resistance was determined.

Scope

32. The laboratory investigation was conducted in two phases. The primary purpose of Phase I was to determine the compatibility of each AWA with each HRWR, and to determine an estimate for the optimum amount of each admixture. Thirty-nine concrete mixtures were batched using combinations of three HRWR's, five AWA's, and three water-cement ratios (W/C). Measurements for slump, air content, washout, and compressive strength were made. A test

matrix for Phase I is shown in Table 1. The five AWA's are referred to as A, B, C, D, and E rather than by their trade names. There is no direct connection between this nomenclature and that used to describe the five classes of AWA's. Information describing the five AWA's is given in Table 2.

33. The primary purpose of Phase II was to determine which mixtures were most suited for making underwater repairs. Secondary purposes of Phase II were to determine if there was any correlation between the two-point measurements and washout, and if the AWA's had any effect upon the strength of abrasion-erosion resistance of the concrete. Many of the better mixtures from Phase I were repeated, and new mixtures that seemed appropriate for evaluation were tested. Fifty mixtures were batched and measured for slump, air content, washout, and two-point workability. Each mixture was also tested for compressive strength and abrasion-erosion resistance. A test matrix for Phase II is shown in Table 3.

34. The results obtained from these tests were used to evaluate the properties needed for concrete to be used for making underwater repairs in areas susceptible to abrasion and erosion, and to determine the usefulness of the two-point workability test in measuring these properties.

PART II: EXPERIMENTAL PROGRAM

35. This chapter summarizes the experimental part of the investigation. Described below are the concrete mixture proportions and test procedures for Phases I and II.

Phase I: Concrete Mixture Proportions

36. Three concrete mixtures having good abrasion-erosion resistance and a high degree of workability were chosen for this phase of the investigation. Tables 4, 5, and 6 show the mixture proportions for 1-cu yd batches. The bulk specific gravities, percent absorption, and net moisture contents of the materials are also given. Mixtures 1Control and 3Control contained 590 lb of cement and with a 15 percent silica fume addition by mass. Mixtures 1Control and 3Control differed only in the W/C, 0.40 and 0.36 by weight, respectively. Mixture 2Control contained 700 lb of cement with a 15 percent silica fume addition and a 15 percent fly ash addition, both by mass. The W/C for mixture 2Control was 0.32 by mass. An American Society for Testing and Materials (ASTM) C 150 Type I cement was used for all mixtures. An ASTM C 618 Class F fly ash was used in mixture 2Control. The coarse aggregate was 25.0-mm (1-in.) nominal maximum size chert gravel, and the fine aggregate was a natural chert sand. Table 7 contains the results of a sieve analysis of the fine and coarse aggregates. Tables 8, 9, and 10 contain the results of chemical and physical tests on the cement, fly ash, and silica fume.

37. All additional mixtures were identical to mixtures 1Control, 2Control, and 3Control except for the type and amount of HRWR and AWA. Three HRWR's having different chemical compositions--naphthalene, melamine, and a synthetic polymer--were used to enhance the workability. Five AWA's were used to enhance the cohesiveness of the mixtures.

38. The batching sequence for the aggregates, cement, and water was according to ASTM C 192-81. The mixing sequence was continuous. The HRWR was added after approximately 30 sec of mixing. The HRWR was added in increments until an 8 ± 1 -in. slump was attained. The AWA was added after the HRWR and in small increments until a noticeable loss in workability occurred. If necessary, the mixtures were then redosed with HRWR to maintain the high

slump. The batch size was 1.5 cu ft. Pertinent information for all concrete mixture proportions is given in Tables 11 and 12.

Phase I: Test Procedures

39. The slump (ASTM C 143-78), air content (ASTM C 231-82), unit weight (ASTM C 138-81), and washout (Appendix A) were measured on each mixture. Three 4-in.-diam by 8-in.-high cylindrical specimens were cast according to ASTM C 192-81. These specimens were tested in compression according to ASTM C 39-84 at 28-day age. Ten abrasion-erosion specimens were cast from mixtures 1Control, 2Control, and 3Control and tested according to CRD-C 63-80 beginning at 28-day age. Both top and bottom surfaces were tested. A statistical analysis upon these specimens was used to determine the surface having the smallest amount of variation and the number of specimens necessary for testing at a 90-percent confidence level. The results of this analysis is given in Appendix C. The volume loss per unit surface area was measured rather than the mass loss as prescribed in CRD-C 63-80. This makes it possible to compare results from specimens less than 4 in. high to standard size specimens. Testing specimens shorter than 4 in. was not necessary in this program, but it was expected to be necessary in later experiments.

Phase II: Concrete Mixture Proportions

40. Many of the better mixtures from Phase I were repeated. Additional mixtures were also tested. Mixture 13Control contained 549 lb of cement with an 11-percent silica fume addition and an 11-percent fly ash addition, both by mass. The W/C was 0.42 by mass. The mixture proportions for Mixture 13Control are given in Table 13. The mixture was adapted from work done by Maage and Hjøllø (1983). Two tremie mixtures were adapted from work done by Gerwick, Holland, and Komendant (1981). The mixture proportions are given in Tables 14 and 15. A fourth HRWR, lignosulfonate, was added to the program. Batching and mixing were the same as in Phase I, and the batch size was 2.0 cu ft. Pertinent information for all concrete mixtures is given in Tables 16 and 17.

Phase II: Test Procedures

41. The slump, air content, unit weight, washout, and two-point workability (Appendix B) were measured for each mixture. Three 4-in.-diam by 8-in.-high cylindrical specimens and three abrasion-erosion specimens were cast. Compressive strength testing was performed at 28-day age. Some specimens were not tested until a later age due to a scheduling mistake. The abrasion-erosion testing began at 28-day age. The testing for some of these specimens was delayed due to a limited number of units of test apparatus.

PART III: TEST RESULTS AND DISCUSSION

42. The results from all tests are presented and discussed in this part. The results from Phase I include measurements of slump, air content, washout, and compressive strength. The results from Phase II include slump, air content, washout, two-point workability and compressive strength.

Phase I: Concrete Mixtures

Control mixtures

43. Control mixtures were made without an AWA. The mixtures with melamine HRWR were more resistant to washout than were the mixtures with naphthalene and synthetic polymer HRWR. The data are given in Tables 18 and 19. Plots of the washout data are shown in Figures 8, 9, and 10.

Naphthalene HRWR

44. The first batches of concrete were made using a naphthalene HRWR. The W/C was 0.36. The initial slump of all mixtures was 8 ± 1 in. AWA was then added in small increments. Small dosages of A, D, and E caused a drastic stiffening in the mixture. The slump was 0 to 1 in. More HRWR was added to increase the slump to nearly the original value. AWA's B and C caused an initial stiffening of the mixture. However, the slump returned to nearly the original value with an additional 3 to 5 min of mixing time. A large amount of entrained air was generated with the additions of A, B, and C. Addition of the AWA did not improve the washout resistance of the concrete. With the exception of D, the amount of mortar lost in the washout test was higher for the mixtures containing AWA than for the control mixture that did not contain AWA. This could have been caused, in part, by the high air contents. The data are given in Tables 18 and 19. A plot of the washout data is shown in Figure 11.

Melamine HRWR

45. Unlike the concrete mixtures containing naphthalene HRWR, the addition of small doses of AWA did not cause a significant loss in slump to these concretes containing melamine HRWR.

- a. W/C = 0.36. A large amount of entrained air was generated with the addition of A. An air-detraining agent, D-Air 1, was used in the remaining mixtures to reduce the air contents. Addition of the AWA did improve the washout resistance of the concrete.

With the exception of C, the amount of mortar lost in the washout test was less for the mixtures containing AWA than for the control mixture that did not contain AWA. The data are given in Table 18. A plot of the washout data is shown in Figure 12.

- b. W/C = 0.32. The air-detraining agent was used to reduce the air contents. Addition of A and D improved the washout resistance of the concrete; addition of B and C did not improve the washout resistance of the concrete; addition of E lessened the washout resistance of the concrete, compared to the control mixture that did not contain AWA. The data are given in Table 18. A plot of the washout data is shown in Figure 13.
- c. W/C = 0.40. The air-detraining agent was used to reduce the air contents. Addition of A, C, and D improved the washout resistance of the concrete; addition of B and E did not improve the washout resistance of the concrete, compared to the control mixture that did not contain AWA. The data are given in Table 18. A plot of the washout data is shown in Figure 14.

Synthetic polymer HRWR

46. Addition of AWA to mixtures containing a synthetic polymer HRWR caused a loss of slump in the concretes tested. However, in some concretes the slump loss was not as significant as with the concretes containing naphthalene HRWR.

- a. W/C = 0.36. Addition of A and E caused a drastic stiffening in the mixture. The slump was 0 to 1 in. More HRWR was added to increase the slump. Addition of B, C, and D caused an initial stiffening of the mixture, but the slump returned to nearly the original value with an additional 3 to 5 min of mixing time. Addition of the air-detraining agent, D-Air 1, seemed to increase the slump of the mixtures with B, C, and E, but did not reduce the air content. The air content was reduced by the addition of a fatty-acid air-detraining compound from Diamond Shamrock. With the exception of B, the amount of mortar lost in the washout test was less than for the control mixture without AWA. The data are given in Table 19. A plot of the washout data is shown in Figure 15.
- b. W/C = 0.40. There was a slump loss in all mixtures when AWA was added. Addition of A, C, and E improved the washout resistance of the concrete; addition of B and D did not improve the washout resistance of the concrete, compared to the control mixture without AWA. The data are given in Table 19. A plot of the washout data is shown in Figure 16.

Phase I: Compressive Strength

47. The scheduling mistakes of compressive strength tests made a statistical analysis impractical. As a result, a statistical analysis was not

performed on these data. The compressive strength data are presented in Tables 18 through 21.

Phase II: Concrete Mixtures

Naphthalene HRWR

48. Mixture 3Control (W/C = 0.36) was repeated. This mixture was also repeated with the addition of AWA's C and D. The results were the same as those in Phase I. The data are given in Table 20. A plot of the washout data is shown in Figure 17. A plot of the two-point workability is shown in Figure 18. Plots of the abrasion-erosion data are shown in Figures 19 and 20.

Melamine HRWR

49. Mixture 6Control (W/C = 0.36) was repeated. Mixtures were also repeated using each of the five AWA's. The dosage rates were similar to those used in Phase I. D-air 1 was used in each mixture except the control mixture. Some difficulty was encountered in obtaining a set of points with a good correlation coefficient (>0.990) from the two-point workability test. The mixture was repeated once again when the correlation coefficient was less than 0.990. As noted in Phase I, there was less washout in the mixtures with melamine HRWR than those with naphthalene HRWR. The "g" value of the two-point workability test was higher for the mixtures with melamine HRWR than for those with naphthalene HRWR. The data are given in Table 20. Plots of the washout data are shown in Figures 21 and 22. A plot of the two-point workability data is shown in Figure 23. Plots of the abrasion-erosion data are shown in Figures 24 through 29.

Lignosulfonate HRWR

50. Lignosulfonate HRWR was added to the evaluation because of its potential to increase the potlife of the concrete mixtures. Lignosulfonate used at high dosages does have a retarding effect. D-Air 1 was used to lower the air content of the concrete. Mixtures were repeated when the correlation coefficient of the data points from the two-point workability test was less than 0.990.

- a. W/C = 0.36. Addition of the AWA's caused a slight reduction in slump. A small addition of HRWR was added to maintain the

original slump. Addition of the AWA's did not improve the washout resistance of the concrete. Addition of E lessened the washout resistance of the concrete, compared with the control mixture (12Control) that did not contain AWA. The "g" value of the two-point test was similar to those values of the concrete mixtures containing melamine HRWR. The data are given in Table 21. Plots of the washout data are shown in Figures 30 and 31. A plot of the two-point data is shown in Figure 32. Plots of the abrasion-erosion data are shown in Figures 33 through 38.

- b. W/C = 0.32. Addition of the AWA's caused a slight reduction in slump. A small addition of HRWR was added to maintain the original slump. The addition of each AWA improved the washout resistance of the concrete compared with the control mixture (11Control) that did not contain AWA. The "g" values of the two-point workability test were less than those values of the concretes having a W/C = 0.36 and containing melamine or lignosulfonate HRWR, but higher than those values of the concretes having naphthalene HRWR. The data are given in Table 21. A plot of the washout data is shown in Figure 39. A plot of the two-point data is shown in Figure 40. Plots of the abrasion-erosion data are shown in Figures 41 and 42.
- c. W/C = 0.40. The addition of A improved the washout resistance of the concrete; addition of B, C, D, and E lessened the washout resistance of the concrete, compared with the control mixture (14Control) that did not contain AWA. The "g" values of the two-point test were similar to those values of the concretes having a W/C = 0.32 and containing lignosulfonate HRWR. The data are given in Table 21. A plot of the washout data is shown in Figure 43. A plot of the two-point workability data is shown in Figure 44. Plots of the abrasion-erosion data are shown in Figures 45 through 50.
- d. W/C = 0.42. The addition of all AWA's except C caused a slight reduction in slump. Additional HRWR was added to maintain the original slump. The addition of all AWA's except E improved the washout resistance of the concrete; addition of E lessened the washout resistance of the concrete, compared with the control mixture (13Control) that did not contain AWA. The "g" values of the two-point workability test were similar to those values of the concretes having a W/C = 0.36 and containing lignosulfonate HRWR. The data are given in Table 21. A plot of the washout data is shown in Figure 51. A plot of the two-point data is shown in Figure 52. Plots of the abrasion-erosion data are shown in Figures 53 through 58.

Conventional tremie concrete

51. Two concrete mixtures containing 705 lb of cement with W/C = 0.45 and 0.42, and two mixtures containing 353 lb of cement, 353 lb of fly ash, with W/C = 0.40 and 0.38 were evaluated without AWA's. The washout resistance of these concrete mixtures was substantially less than any of the mixtures

evaluated above. The "g" values of the two-point workability test were similar to those values of the mixtures containing naphthalene HRWR. The data are given Table 21. A plot of the washout data is shown in Figure 59. A plot of the two-point workability data is shown in Figure 60. Plots of the abrasion-erosion data are shown in Figures 61 through 64.

PART IV: ANALYSIS

52. In this part the results of a statistical analysis are presented and discussed. The effects that the properties of the concrete mixtures have upon the washout and abrasion-erosion characteristics were examined. A relationship between washout and two-point workability was examined.

Washout

53. The washout data collected in Phases I and II were grouped together and evaluated using the Statistical Analysis System (SAS) (SAS 1982) on the IBM 4331 computer at WES. Eighty-six observations were in the data set and are listed in Table 22. An analysis of variance indicated that the washout characteristics of concrete are affected by the W/C, AWA, and HRWR, with probabilities of 0.0001, 0.0085, and 0.0001, respectively, that the relationship does not exist. Indications are that the presence of fly ash does not have a significant effect upon the washout characteristics of the concrete. There was insufficient data to reach a conclusion concerning the effects of silica fume upon the washout characteristics of the concrete. It should be noted that all forthcoming conclusions concerning the effects of fly ash and silica fume are based on limited data, and therefore, are subject to error. A plot of washout verses AWA, shown in Figure 65, illustrates that the mixtures containing AWA were more consistent in having low washout losses than were the mixtures that did not contain AWA. None of the five AWA's tested stood out as being significantly more or less effective in preventing washout of the cement paste.

54. A plot of washout versus HRWR, shown in Figure 65, illustrates that the mixtures containing melamine and lignosulfonate were more consistent in having low washout losses than were the mixtures containing naphthalene, synthetic polymer, and HCA. It should be noted, however, that the mixtures containing HCA did not contain AWA. This accounts, at least in part, for the high washout values for these mixtures.

55. A plot of washout versus W/C, shown in Figure 66, illustrates that mixtures having lower W/C were more consistent in having low washout losses than were the mixtures having higher W/C. Larger doses of AWA could make the mixtures with higher W/C more resistant to washout. Very small doses of AWA

were used with the lower W/C due, in part, to the increased cohesiveness resulting from the low W/C.

56. Duncan's multiple range test further enforces the conclusion that the washout characteristics are influenced by AWA. The grouping, shown in Figure 67, suggests that the mixtures with any of the five AWA's have less washout than the mixtures without AWA. It also indicates that one AWA, E, could be less effective than the other four.

57. Duncan's test for W/C reaffirms the conclusion that mixtures with lower W/C have less washout. The grouping is shown in Figure 68. This grouping is biased in that only one mixture has a W/C of 0.45 and one mixture with a W/C of 0.38. Neither of these mixtures contain AWA.

58. Duncan's test for HRWR reaffirms the conclusion that mixtures containing melamine and lignosulfonate have lower washout losses than mixtures containing the other HRWR's. The grouping is shown in Figure 69. This grouping is biased in that only four mixtures contain HCA, and none of these mixtures contain AWA.

59. Duncan's test also suggests, with the limited data available, that concrete mixtures could be more resistant to washout when silica fume is present in the mixture. Logic suggests that mixtures containing silica fume should be more resistant to washout since, according to Ramachandran (1984), it is a form of AWA.

60. The results of the Duncan's tests, including means, number of samples, and groupings for AWA, W/C, HRWR, silica fume, and fly ash, are given in Tables 23, 24, 25, 26, and 27, respectively.

Two-Point Workability

61. The "g" and "h" values from the two-point workability test were paired with the washout data from each respective test. Thirty-seven data points were used in the evaluation and are listed in Table 28. Values of "g" and "h" from lines having a low correlation coefficient were not used if the mixture was repeated and a line having a better correlation coefficient was obtained. Only the points from the better line were used. The data were fitted to nine curves with a curve-fit program (Renner 1979) in the Honeywell computer system at WES. A relationship could not be established between washout and the "h" value. The data indicate that there could be a relationship

between washout and the "g" value. A nonlinear correlation coefficient greater than 0.80 was obtained for three curves--common log1, common log2, and 3rd degree polynominal. Plots of these three curves are shown in Figures 70, 71, and 72, respectively. Equations and residual values are presented in Tables 29, 30, and 31, respectively. While more data are needed to confirm this relationship, it is reasonable to believe that a relationship does exist since it was suggested earlier (Rixom 1978) that the "g" value should be related to the cohesion of the concrete. The data indicate that as the "g" value increases, or as the concrete becomes more cohesive, the washout of the concrete decreases.

Abrasion-Erosion Data

62. The abrasion-erosion data from Phase I and Phase II were grouped together and evaluated using SAS. Ninety-five points were in the data set and are listed in Table 32. An analysis of variance indicated that the abrasion-erosion characteristics of concrete are affected by the W/C, HRWR, and fly ash, with probabilities of 0.005, 0.0132, and 0.0001, respectively, that the relationship does not exist. The data indicate that AWA does not have a significant effect upon the abrasion-erosion condition. As with the evaluation of washout, there is a limited amount of data from which one can draw conclusions concerning the effects of fly ash and silica fume. Any effects that the W/C and HRWR have upon the abrasion-erosion characteristics of concrete are not obvious in the plots of abrasion-erosion data versus W/C and HRWR, shown in Figures 73 and 74, respectively.

63. Duncan's test also indicates that the abrasion-erosion characteristics of concrete are affected by W/C, HRWR, and fly ash. The test gives no indication that AWA affects the abrasion-erosion characteristics of concrete. The groupings are shown in Figures 75, 76, and 77 for AWA, W/C, and HRWR, respectively. The results, including means, number of samples, and groupings, for AWA, W/C, HRWR, fly ash, and silica fume are given in Tables 33, 34, 35, 36, and 37, respectively.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

64. A series of concrete mixtures were proportioned to be suitable for placing underwater and to have high washout and abrasion-erosion resistance. A combination of low W/C, high cement contents, fly ash, and silica fume were used to increase the abrasion-erosion resistance of the concrete. AWA's were used to enhance the resistance of the concrete to washout. The concrete mixtures were tested for slump, air content, washout, two-point workability, compressive strength, and abrasion-erosion resistance. The results of these tests provide guidance in selecting the proper concrete mixtures that have improved abrasion-erosion resistance and are suitable for placement underwater in thin lifts.

65. Concretes suitable for traditional placements can be unsuitable for placement underwater in thin lifts, especially those having a high W/C. These mixtures can be highly susceptible to washout. However, increased cement and sand contents, common to most concretes traditionally placed underwater, can be essential to placements underwater in thin lifts.

66. Concrete mixtures having low W/C were more resistant to abrasion-erosion. These mixtures also tended to be more resistant to washout.

67. The type of HRWR affects the washout characteristics of the concrete mixtures. The concretes containing melamine and lignosulfonate were more resistant to washout than were the mixtures containing naphthalene, synthetic polymer, and HCA. The type of HRWR also has an effect upon the abrasion-erosion characteristics of the concrete mixtures. The concretes containing naphthalene were more abrasion-erosion resistant than were the mixtures containing the other HRWR's.

68. Concrete mixtures can be made more resistant to washout with the addition of the proper type and amount of AWA. The optimum dosage of AWA was small, and decreased as the W/C decreased. Each of the five AWA's tested demonstrated varying degrees of improvement in washout resistance of the concretes. An excessive amount of AWA can make the concrete mixtures unworkable. In some cases, an additional amount of HRWR can increase the workability of the concretes after being overdosed with AWA. However, this procedure is not recommended. The proper type and dosage of AWA and HRWR should be

determined in trial batches prior to the beginning of any concrete placement. Extreme caution should be exercised if it becomes necessary to adjust the dosage of either the AWA or HRWR. A small change in the dosage can result in a dramatic change in the workability of the concretes. Some of the AWA's tested have not been put on the open market and are classified by the manufacturers as still-in-the-development stage. Although the manufacturers provided WES with small samples for this investigation, it could be difficult to obtain these AWA's in large quantities at this time.

69. Some AWA's and HRWR's can be incompatible. The addition of a very small dosage of any of the five AWA's tested to concretes containing naphthalene caused a dramatic loss in workability. A workable concrete having improved washout resistance could not be obtained using naphthalene with any of the five AWA's tested.

70. There is some evidence that the presence of fly ash in the concrete mixtures can improve both the washout and abrasion-erosion resistance. However, only a small number of concrete mixtures containing fly ash were evaluated. Therefore, this evidence is not conclusive.

71. There is some evidence that the presence of silica fume in the concrete mixtures can improve the washout resistance. However, only a small number of concrete mixtures were evaluated that did not contain silica fume. Therefore, this evidence is not conclusive.

72. The two-point workability apparatus can be a useful tool in measuring some properties of fresh concretes, but it cannot be used alone. The results from this test can be used to identify mixtures that are likely to be resistant to washout. As the "g" value from this test increases, the concretes become more cohesive, and as a result, more resistant to washout. However, if the concrete becomes too cohesive, the workability will begin to decrease.

73. The results of this investigation support the statement by Gerwick et al. (1981) that "there is no single test which will provide definitive data on the workability of a concrete mixture."

Recommendations

74. Testing is recommended for additional concrete mixtures that contain higher cement contents and fly ash and that do not contain silica fume.

It should be determined whether an increased cement content will improve the washout resistance of concrete mixtures; however, more data are needed to establish the effects of fly ash and silica fume conclusively. A determination should be made whether or not these mineral admixtures do improve the washout and abrasion-erosion resistance. Since fly ash is more readily available and inexpensive than silica fume, it should be determined whether fly ash provides benefits equal to silica fume.

75. It is recommended that a future investigation be conducted to determine the placing technique most suitable for making repairs underwater where concrete would be placed in thin lifts. The workability and washout resistance necessary for each placing technique should be decided upon. The two-point workability test should be included in this investigation. It could be possible to establish guidelines for workability and washout using this test.

76. It is recommended that the relationship between the two-point workability test and the washout test be further developed. More data are needed, especially in the concretes having washout values greater than 10 percent, to establish this relationship conclusively.

77. It is recommended that the bonding strength of the repair concrete to the existing concrete be examined. A determination should be made whether the bond is sufficient to prevent hydrostatic uplift or if anchors will be necessary. The effect of washout on the bond should be further determined, and the possibility of establishing guidelines for bond using the washout test should be considered.

REFERENCES

- Bloomer, S. J. 1979. "Further Development of the Two-point Test for the Measurement of the Workability of Concrete," Ph.D. dissertation, University of Sheffield.
- Fox, R. W., and McDonald, A. T. 1978. Introduction to Fluid Mechanics, 2nd ed., Wiley, New York.
- Gerwick, B. C. "Review of the State of the Art for Underwater Repair of Abrasion-Resistant Concrete" (in preparation), US Army Engineer Waterways Experiment Station, Vicksburg, Miss.
- Gerwick, B. C., Holland, T. C., and Komendant, G. J. 1981 (Sep). "Tremie Concrete for Bridge Piers and Other Massive Underwater Placements," Report FHWA/RD-81/153, Federal Highway Administration.
- Komlos, K. 1966. "Penetrator for Testing of Concrete Mix Workability," Stavebnicky Casopis, Vol 14, No. 9, pp 571-572.
- L'Hermite, R. 1951. "Recent Research on Concrete," Annales des Travaux Publics de Belgique, Vol 50, No. 5, (Library Translation Cj. 24, London, Cement and Concrete Association).
- Liu, T. C. 1980. "Maintenance and Preservation of Civil Works Structures; Abrasion-Erosion Resistance of Concrete," Technical Report C-78-4, Report 3, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.
- Maage, M., and Hjøllø O. E. 1983 (Dec). Special Concrete for Underwater Concreting, SINTEF/FCB Report STF65 A83089, SINTEF, The Norwegian Institute of Technology, Trondheim, Norway.
- Makk, O., Tjugum, O., and Westergren, P. 1986. "Pumped Underwater Concrete, Tests on S-me with a Water-Repellent Admixture," Nordisk Betong, Vol 30, No. 1-2, pp 79-82.
- Morinaga, S. 1973. "Pumpability of Concrete and Pumping Pressure in Pipe Lines," Fresh Concrete: Important Properties and Their Measurement, Proceedings, Vol 3, RILEM Seminar held 22-24 March 1973, Leeds, The University, pp 7.3-1 to 7.3-39.
- Murata, J., and Kikukawa, H. 1973. "Studies on Rheological Analysis of Fresh Concrete," Fresh Concrete: Important Properties and Their Measurement, Proceedings, Vol 1, RILEM Seminar held 22-24 March 1973, Leeds, The University, pp 1.2-1 to 1.2-33.
- McDonald, J. E. 1980 (Apr). "Maintenance and Preservation of Concrete Structures; Repair of Erosion-Damaged Structures," Technical Report C-78-4, Report 2, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.
- Nakahara, Y., Ohtomo, T., and Yokota, S. 1976 (Sep). "Development of New Method for Underwater Concreting, KDT Method," Report No. 22, Kajima Institute of Construction Technology, Tokyo, Japan.
- Office, Chief of Engineers, Department of the Army. 1977 (30 Mar). "Repair and Rehabilitation of Stilling Basins," Engineer Circular EC 1110-2-181, Washington, DC.

- Powers, T. C. 1932. "Studies of Workability of Concrete," Journal, American Concrete Institute, Proceedings, Vol 28, pp 419-448.
- Ramachandran, V. S. 1984. Concrete Admixtures Handbook, pp 528-533, Noyes Publications, Park Ridge, N. J.
- Remmer, M., and Henriksen. 1982. "Advanced Concreting Underwater at Large Bridge Site in Denmark," Nordisk Betong, Vol 26, No. 2-4, pp 20-27.
- Renner, R. L. 1979 (Nov). User's Guide for the Interactive Computer Program "Curvefit", Instruction Report 0-79-3, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.
- Rescon A/S. 1983 (Jun). "Underwater Casting with Rescon T-Concrete," Rescon A/S.
- Ritchie, A. G. B. 1967. "The Vane Method of Measuring the Mobility of Fresh Concrete," Conference of British Society of Rheology, Sheffield.
- Rixom, M. R. 1978. Chemical Admixtures for Concrete, Halsted Press, New York, pp 15, 49-50.
- Saluta, M., Yamane, S., Kasami, H., and Sakamoto, A. 1979. "Pumpability and Rheological Properties of Fresh Concrete," Proceedings of Conference on Quality Control of Concrete Structures, held 17-21 June 1979, Swedish Cement and Concrete Research Institute, Stockholm, Vol 2, pp 125-132.
- SAS User's Guide: Statistics, 1982 ed., SAS Institute.
- Schoewert, L. C., and Hillen, H. F. 1972 (Sep). "Underwater Transporting of Concrete with the Hydro-Valve," ACI Journal, pp 584-588.
- Shimizu. "New Underwater Concrete System (NUCS)," Shimizu Technical Abstract.
- Tattersall, G. H. 1971. "Measurement of Workability of Concrete," Conference of the East Midlands Region of the Concrete Society, Nottingham, England.
- _____. 1976. "The Workability of Concrete," The Cement and Concrete Association, London, England.
- Tattersall, G. H., and Banfill, P. F. G. 1983. The Rheology of Fresh Concrete, Pittman Press, Boston, Mass.
- Tattersall, G. H., and Bloomer, S. J. 1979. "Further Development of the Two-Point Test for Workability and Extension of Its Range," Magazine of Concrete Research, Vol 31, No. 109, pp 202-210.
- US Army Engineer Waterways Experiment Station. 1949 (Aug). Handbook for Concrete and Cement, (with quarterly supplements), Vicksburg, Miss.
- US Committee on Large Dams. 1975. "Lessons from Dam Incidents, USA," Committee on Failures and Accidents to Large Dams, American Society of Civil Engineers, New York.
- Uzomaka, O. J. 1974. "A Concrete Rheometer and Its Application to a Rheological Study of Concrete Mixes," Rheologica Acta, No. 13, 1974, pp 12-21.
- Wykeham Farrance. "Two-Point Workability Apparatus, WF-52700, Technical Literature," Wykeham Farrance Engineering, Berkshire, England.

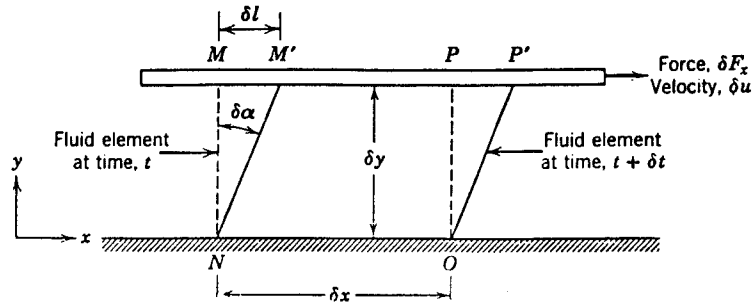


Figure 1. Newton's Law for deformation of a fluid element (Fox and McDonald 1978)

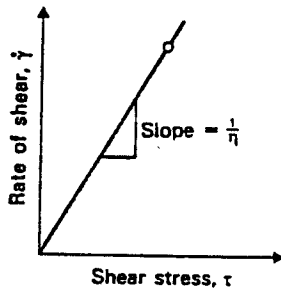


Figure 2. Newtonian liquid:
 $\tau = \eta \dot{\gamma}$ (Tattersall and Banfill 1983)

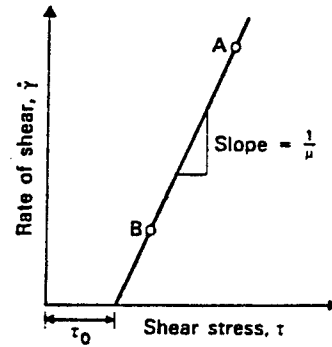


Figure 3. Bingham model:
 $\tau = \tau_0 + \mu \dot{\gamma}$ (Tattersall and Banfill 1983)

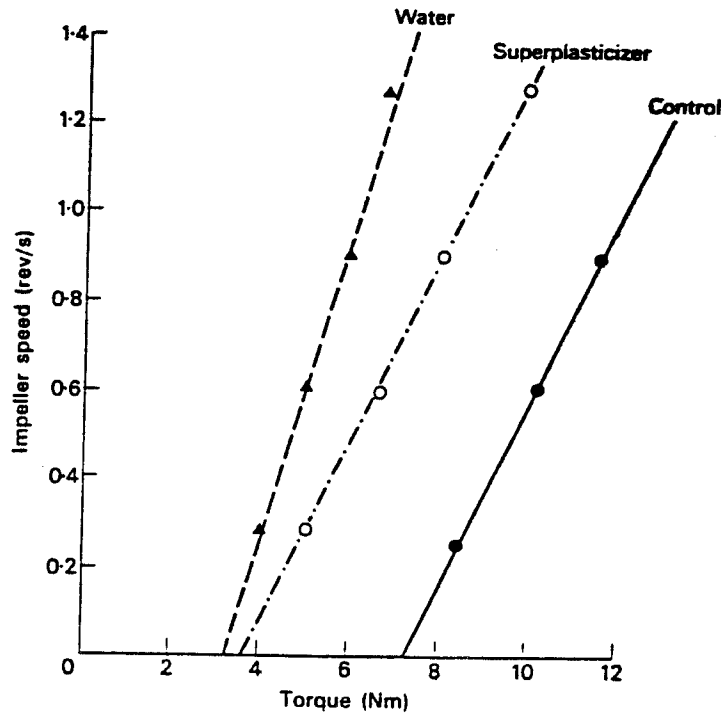


Figure 4. Relative effects of the addition of extra water and of HRWR (Tattersall and Banfill 1983)

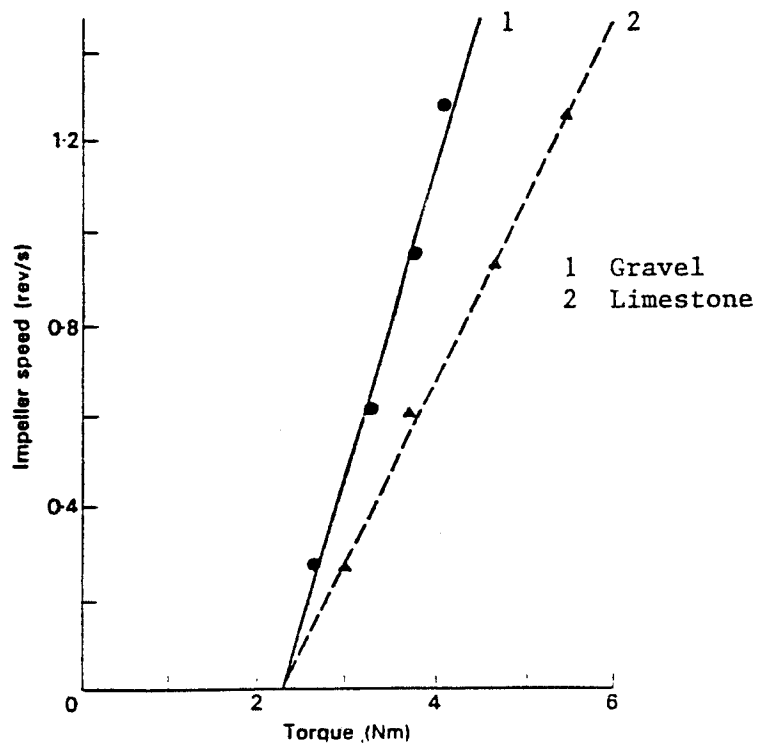


Figure 5. Effect of aggregate type (Tattersall and Banfill 1983)

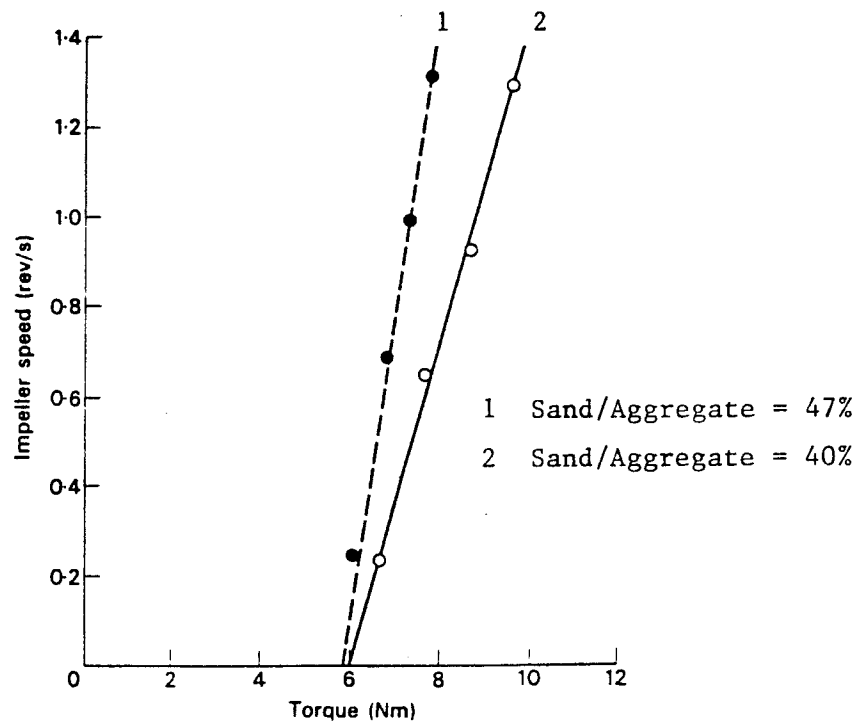


Figure 6. Effect of fines content (Tattersall and Banfill 1983)

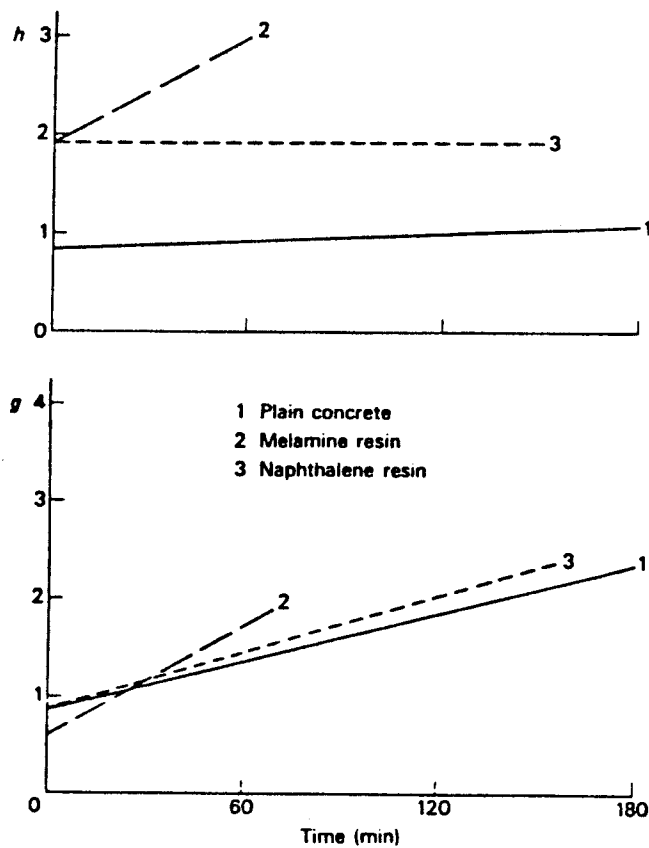


Figure 7. Effect of time after mixing on g and h for mixtures containing HRWR. (Tattersall and Banfill 1983)

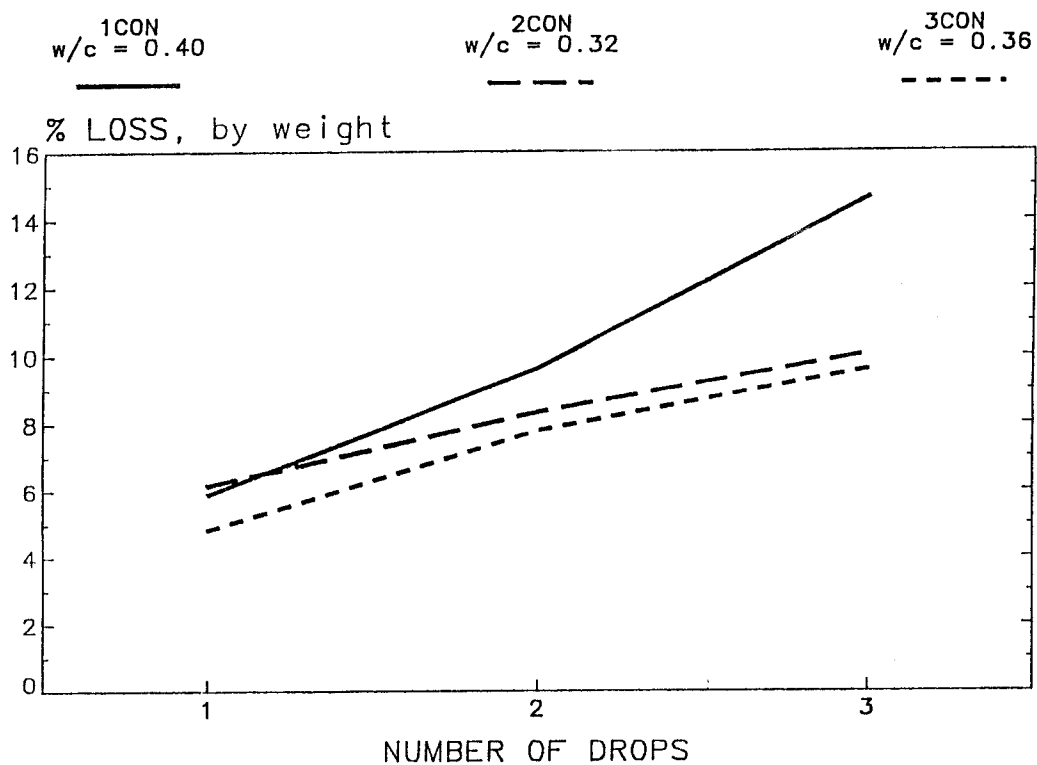


Figure 8. Washout data of control mixtures with naphthalene HRWR

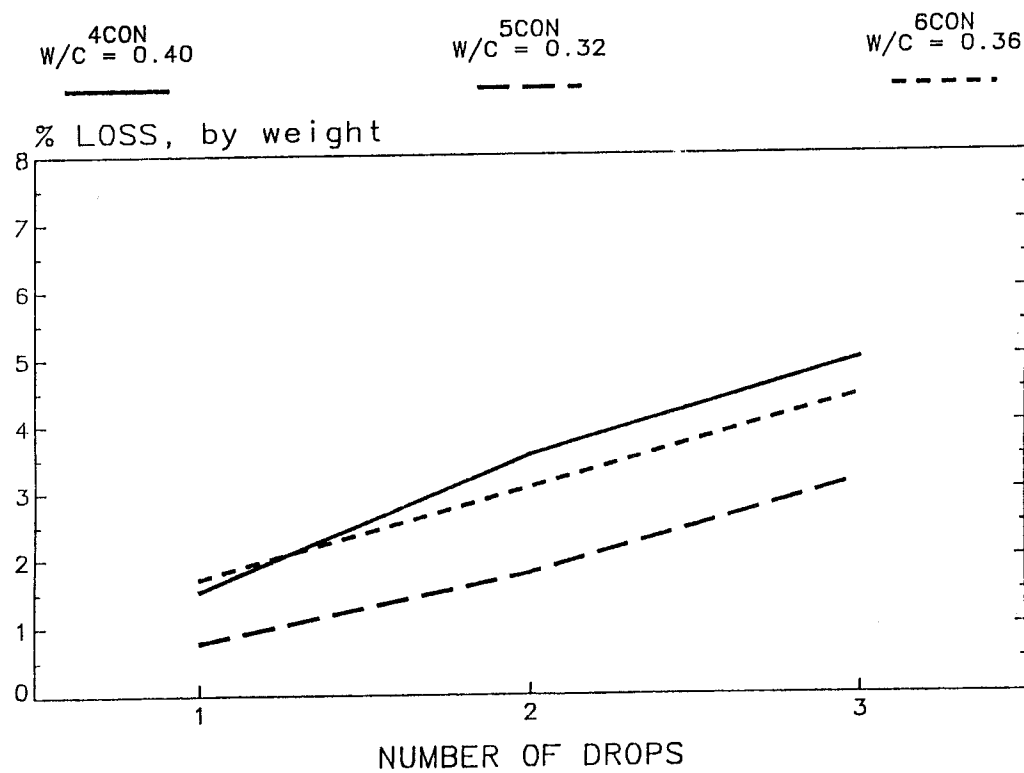


Figure 9. Washout data of control mixtures with melamine HRWR

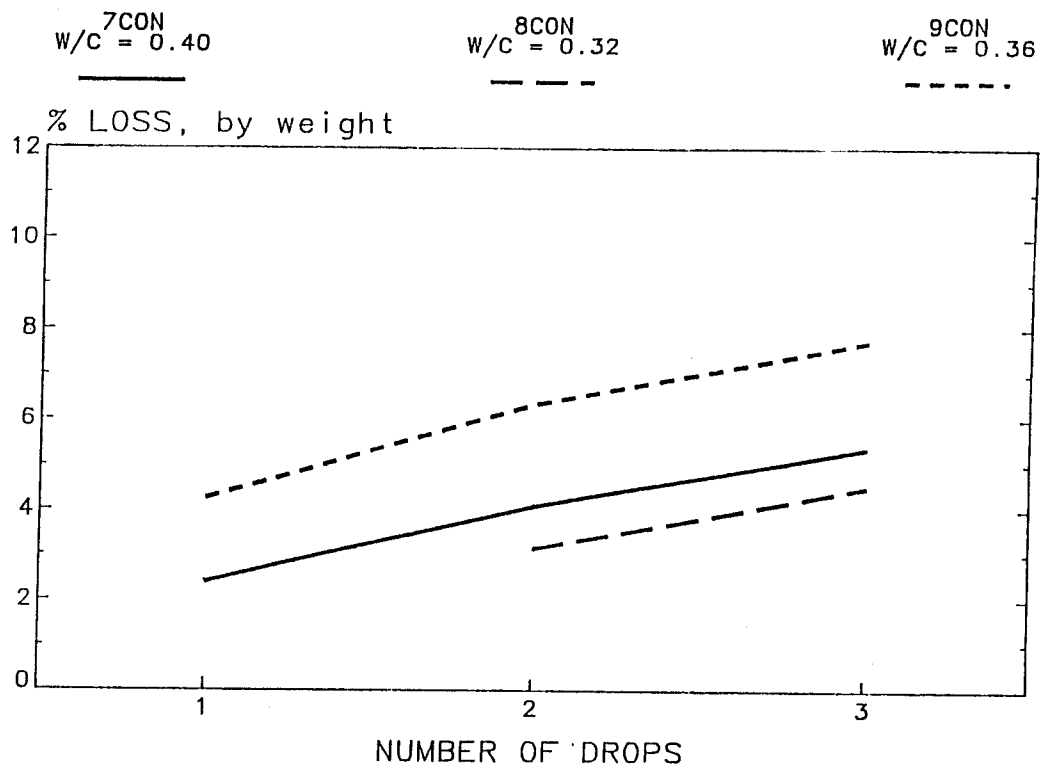


Figure 10. Washout data of control mixtures with synthetic polymer HRWR

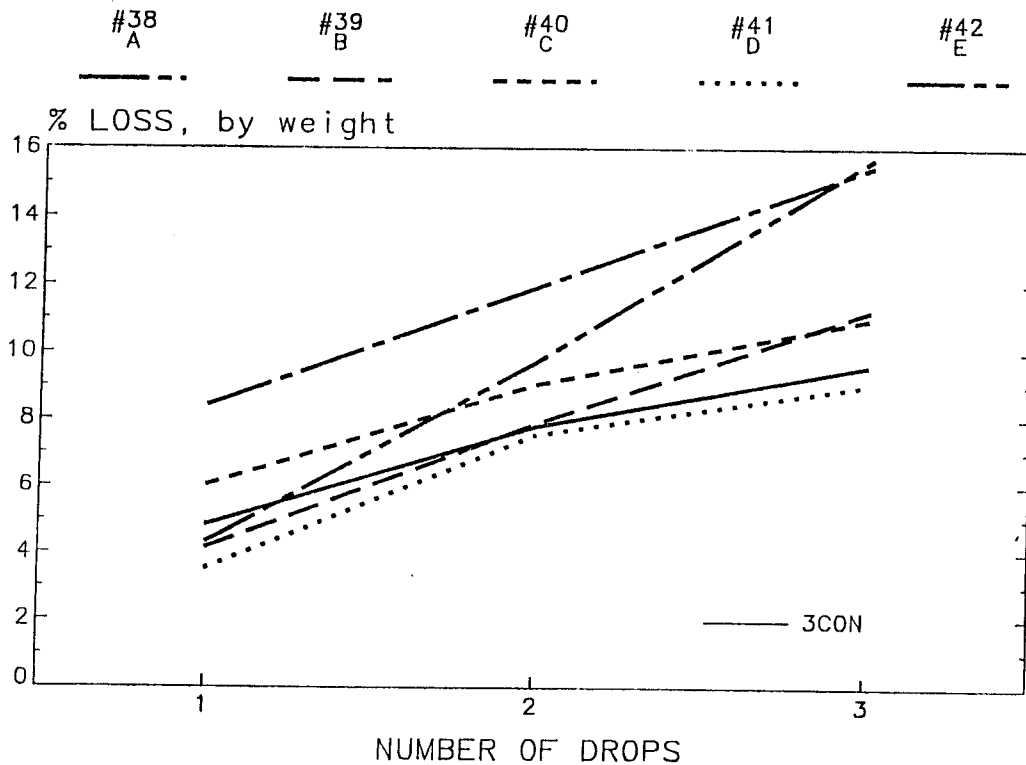


Figure 11. Washout data of mixtures with naphthalene HRWR and W/C = 0.36

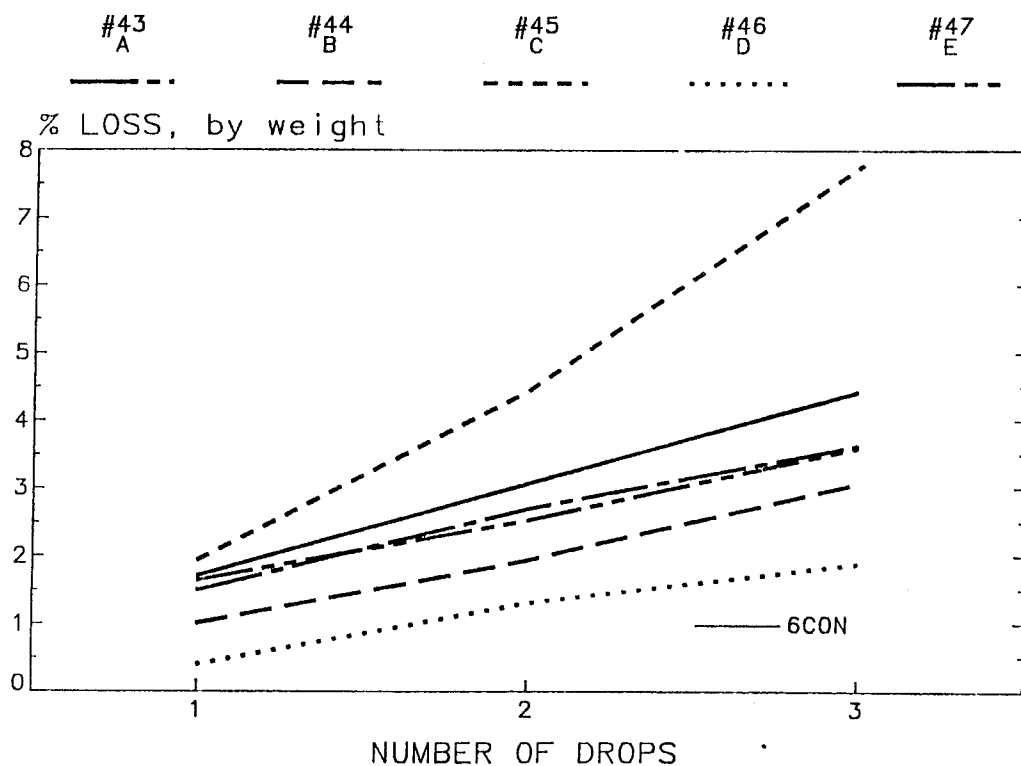


Figure 12. Washout data of mixtures with melamine HRWR and W/C = 0.36

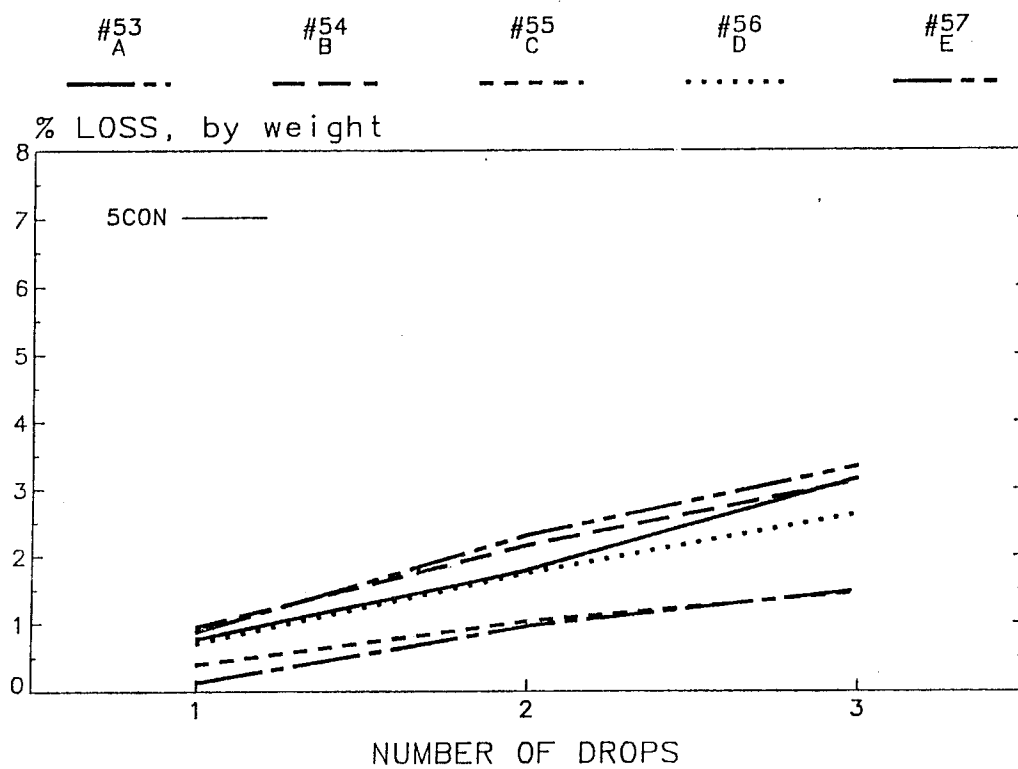


Figure 13. Washout data of mixtures with melamine HRWR and W/C = 0.32

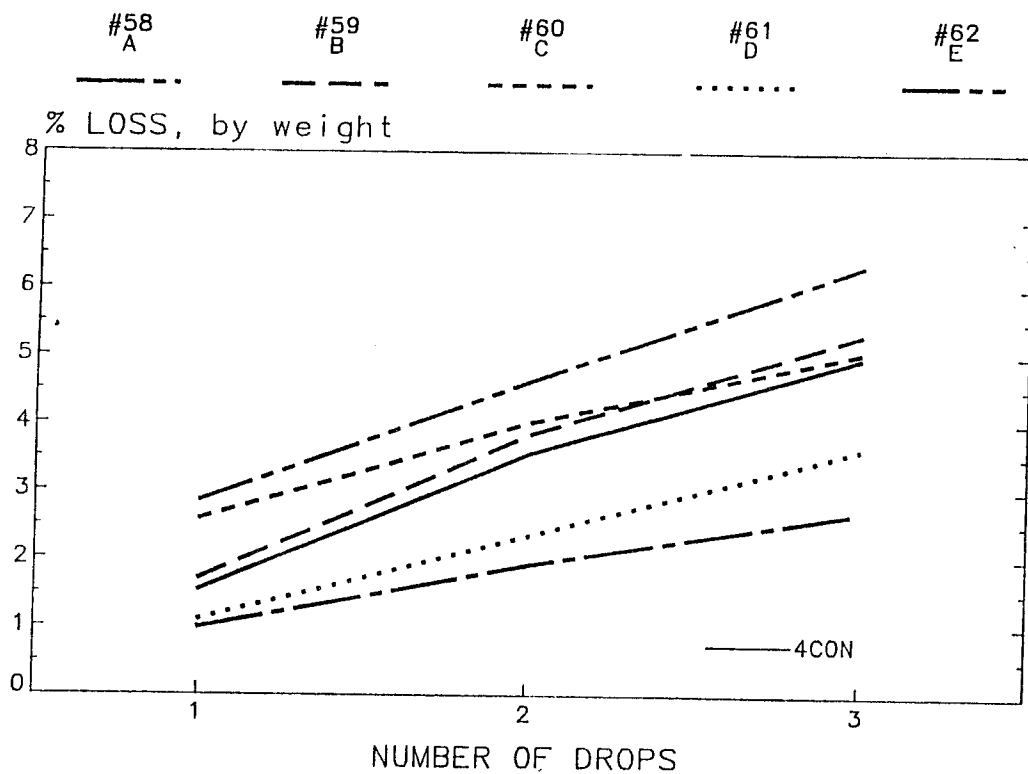


Figure 14. Washout data of mixtures with melamine HRWR and W/C = 0.40

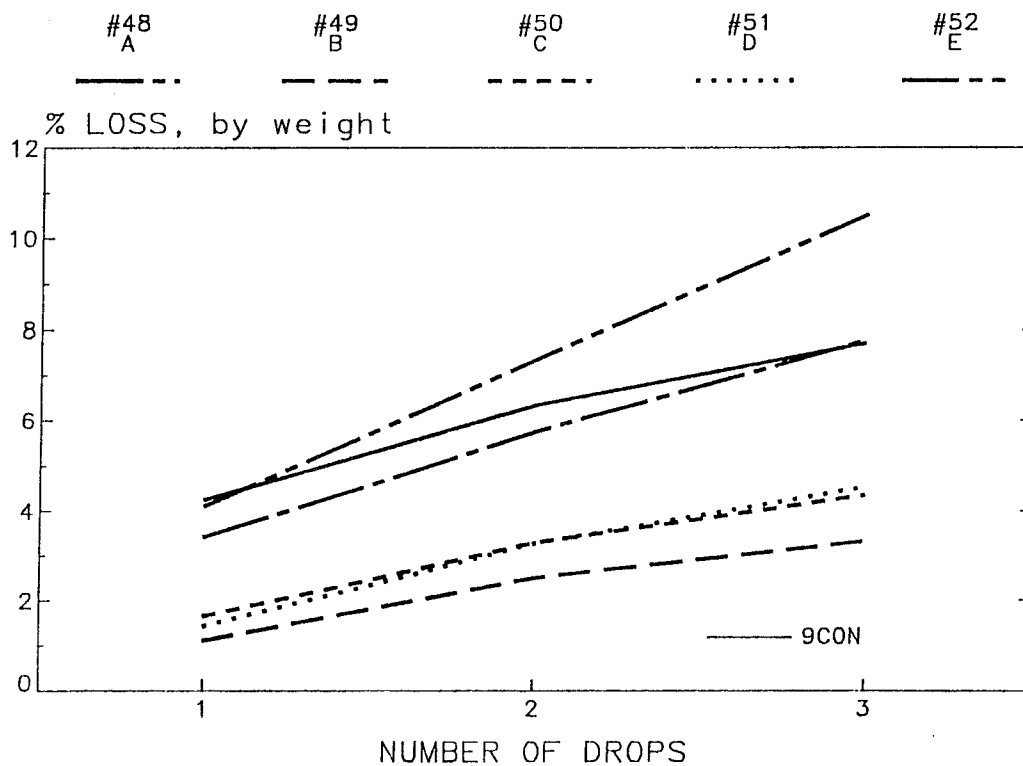


Figure 15. Washout data of mixtures with synthetic polymer HRWR and W/C = 0.36

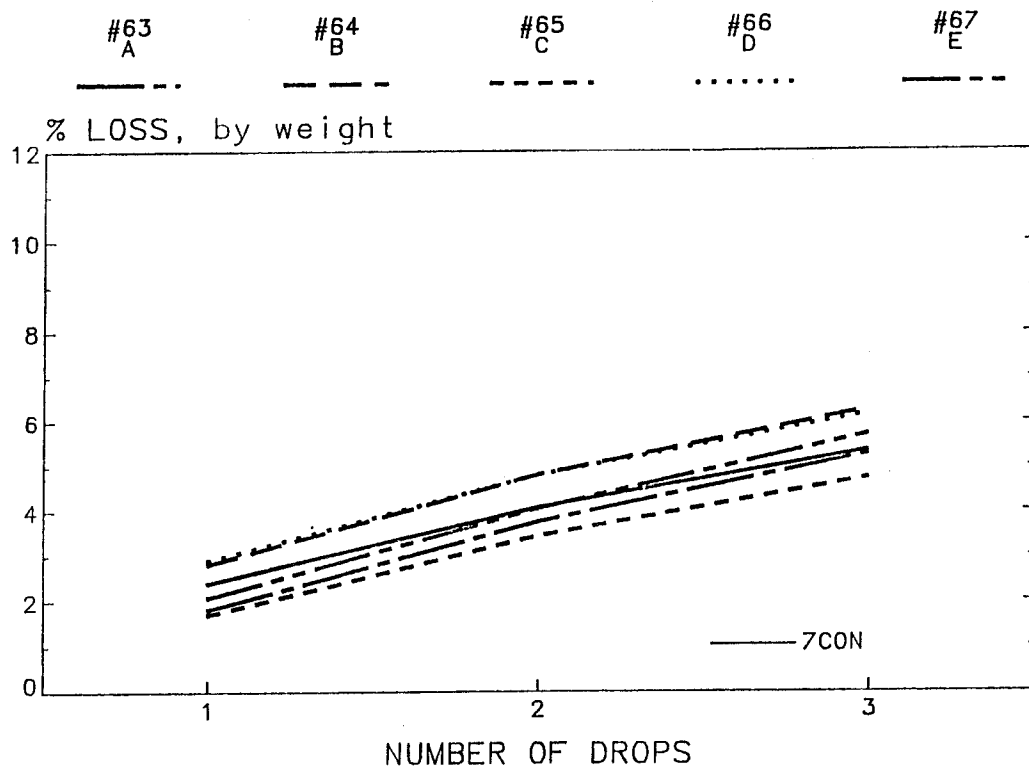


Figure 16. Washout data of mixtures with synthetic polymer HRWR and $W/C = 0.40$

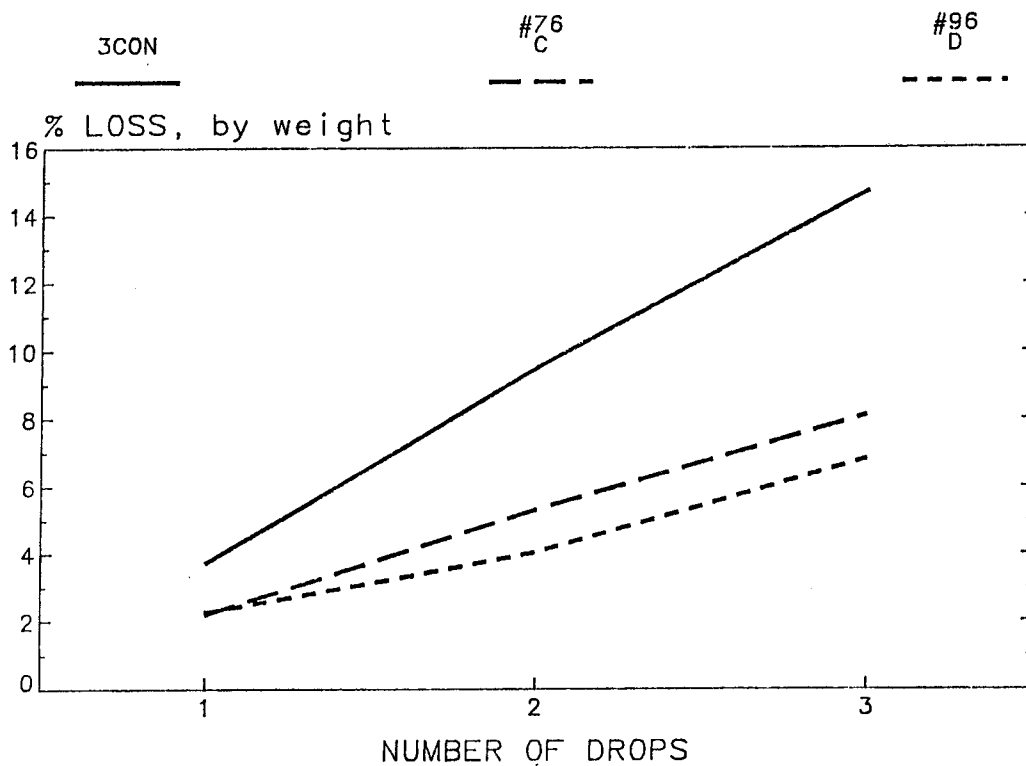


Figure 17. Washout data of mixtures with naphthalene HRWR and $W/C = 0.36$

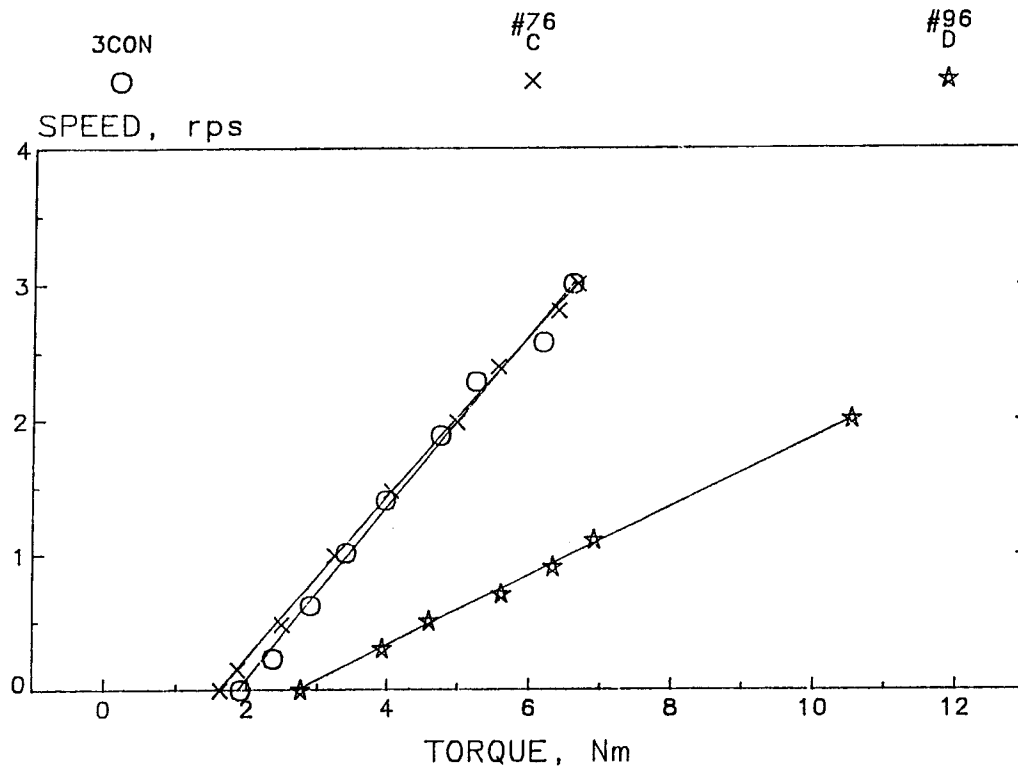


Figure 18. Two-point workability data of mixtures with naphthalene
HRWR and W/C = 0.36

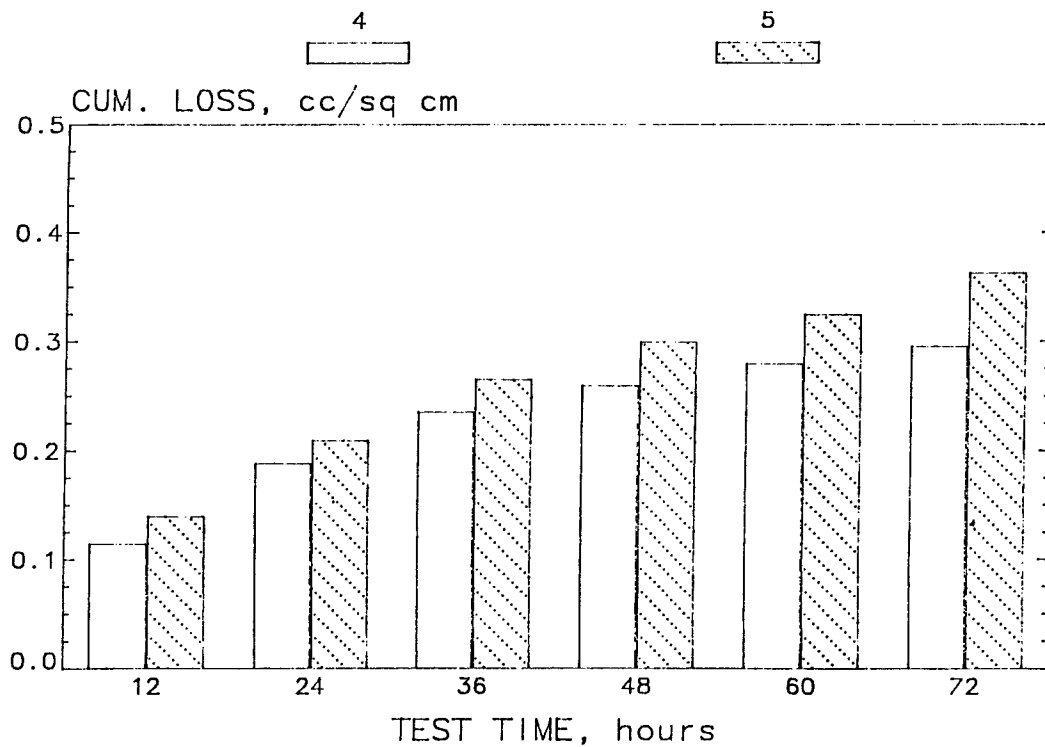


Figure 19. Abrasion-erosion data of mixtures no. 76 with naphthalene
HRWR and W/C = 0.36

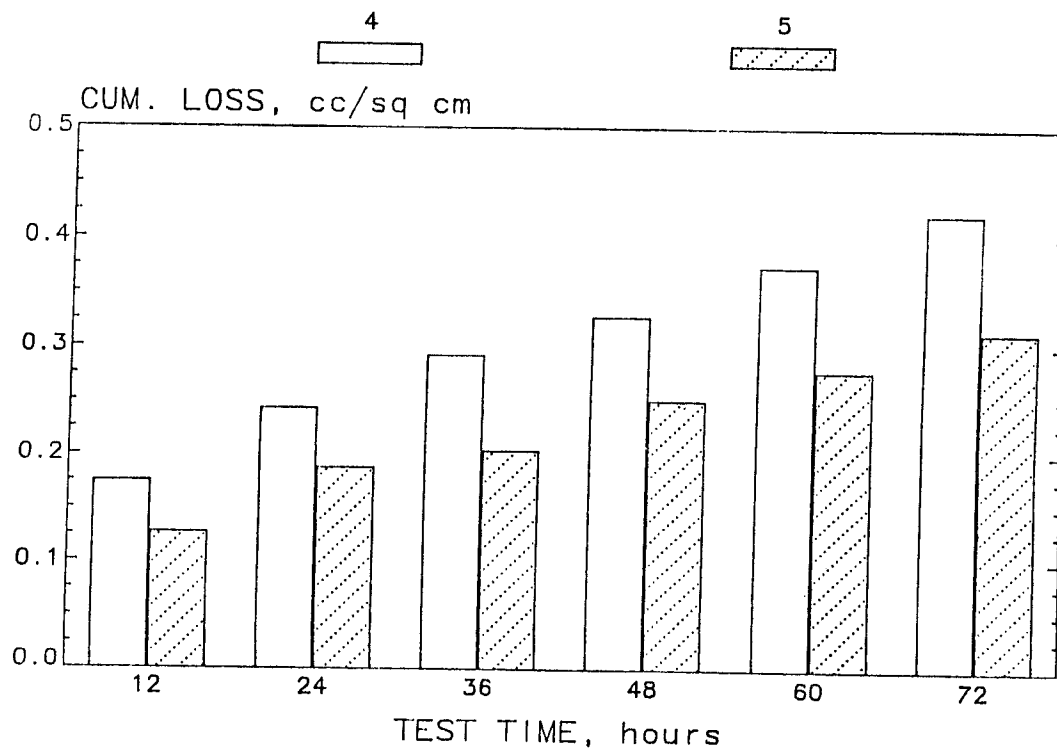


Figure 20. Abrasion-erosion data of mixtures no. 96 with naphthalene HRWR and W/C = 0.36

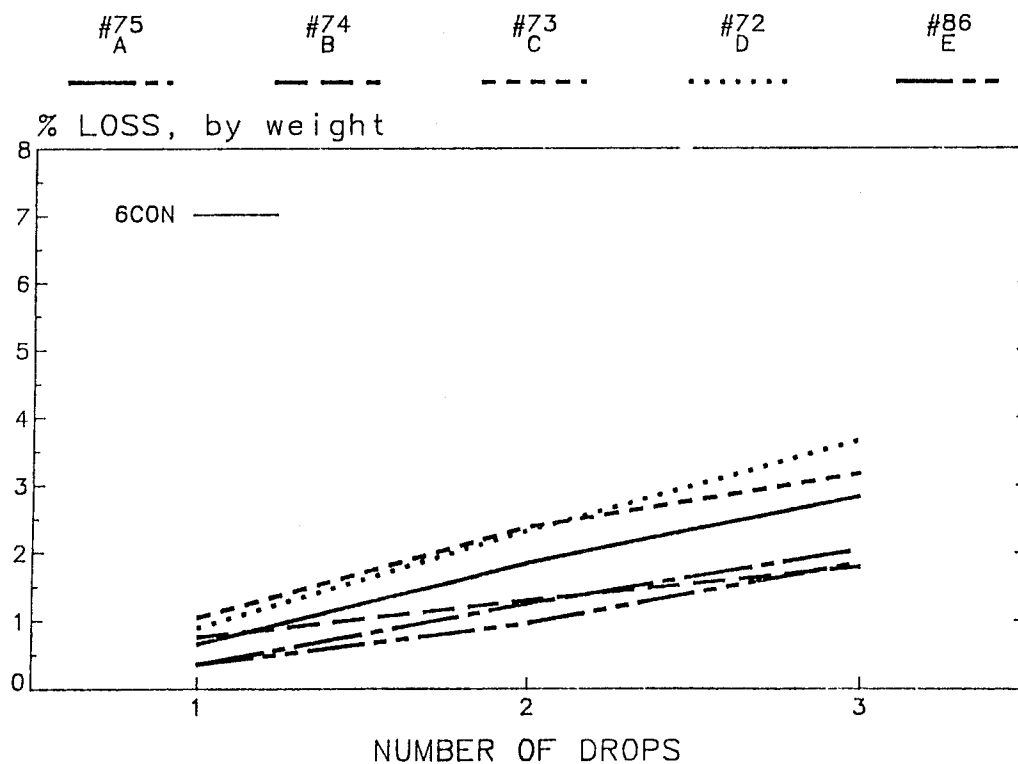


Figure 21. Washout data of mixtures with melamine HRWR and W/C = 0.36

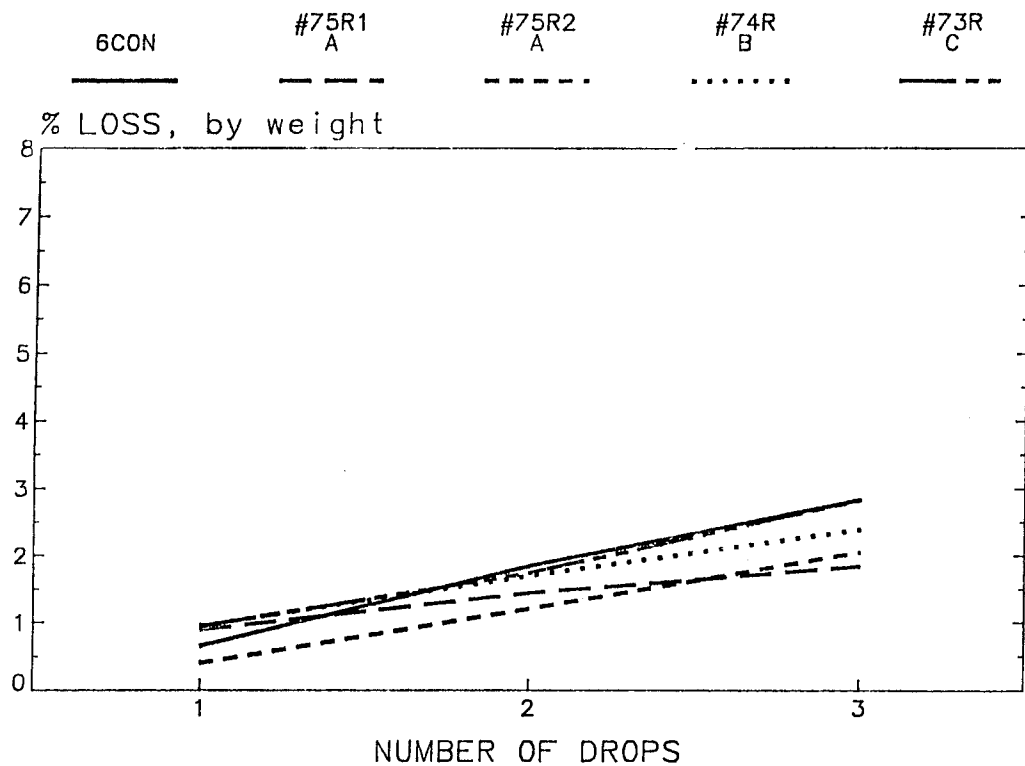


Figure 22. Washout data of additional mixtures with melamine HRWR and $W/C = 0.36$

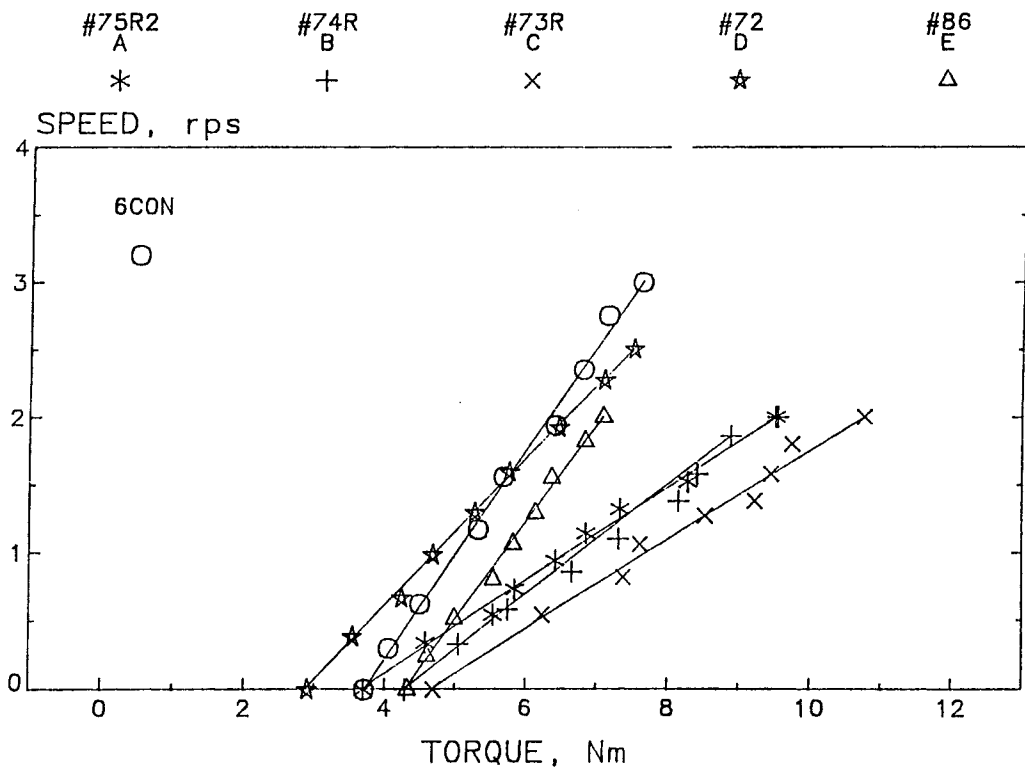


Figure 23. Two-point workability data of mixtures with melamine HRWR and $W/C = 0.36$

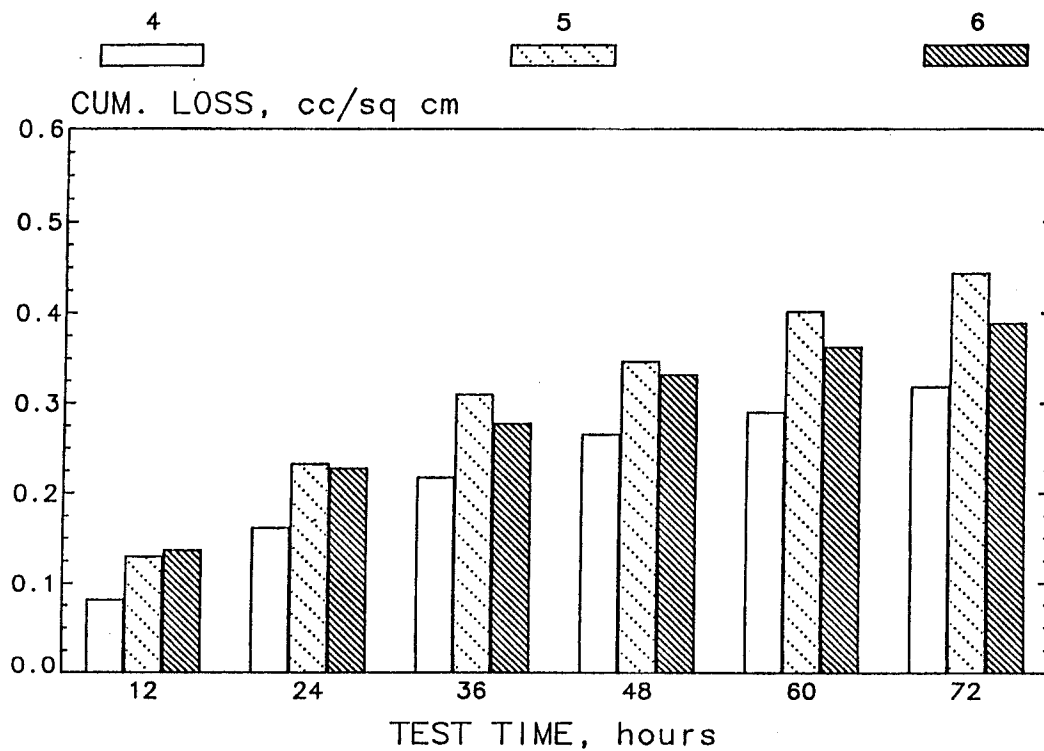


Figure 24. Abrasion-erosion data of mixtures no. 6CON with melamine HRWR and W/C = 0.36

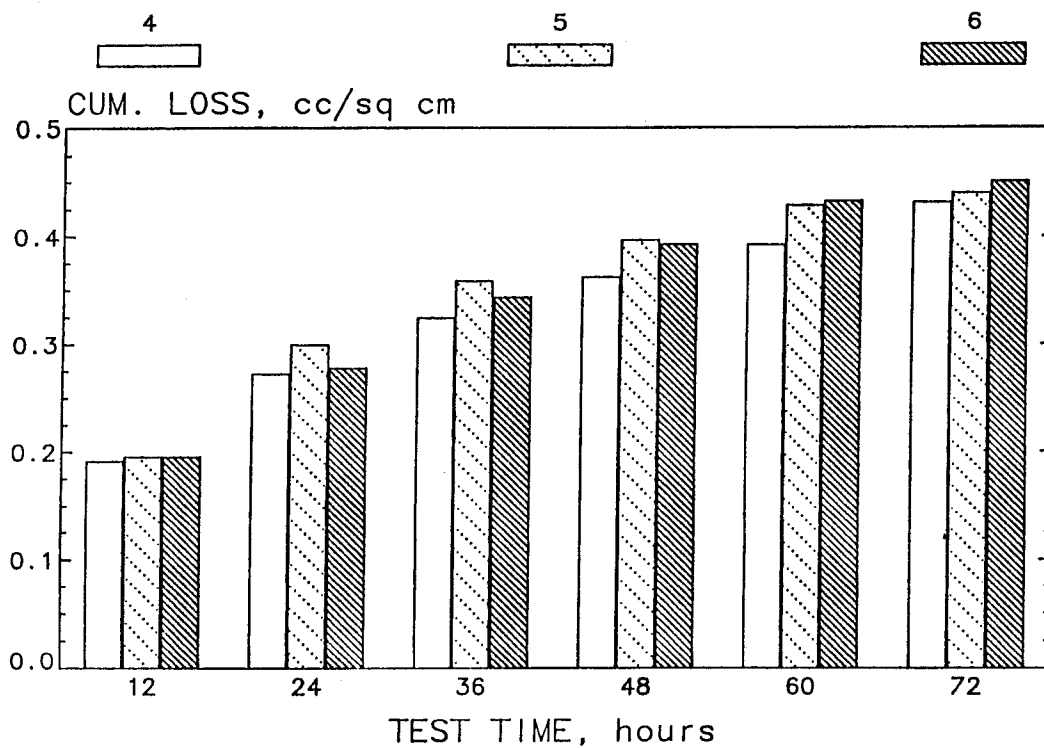


Figure 25. Abrasion-erosion data of mixtures no. 72 with melamine HRWR and W/C = 0.36

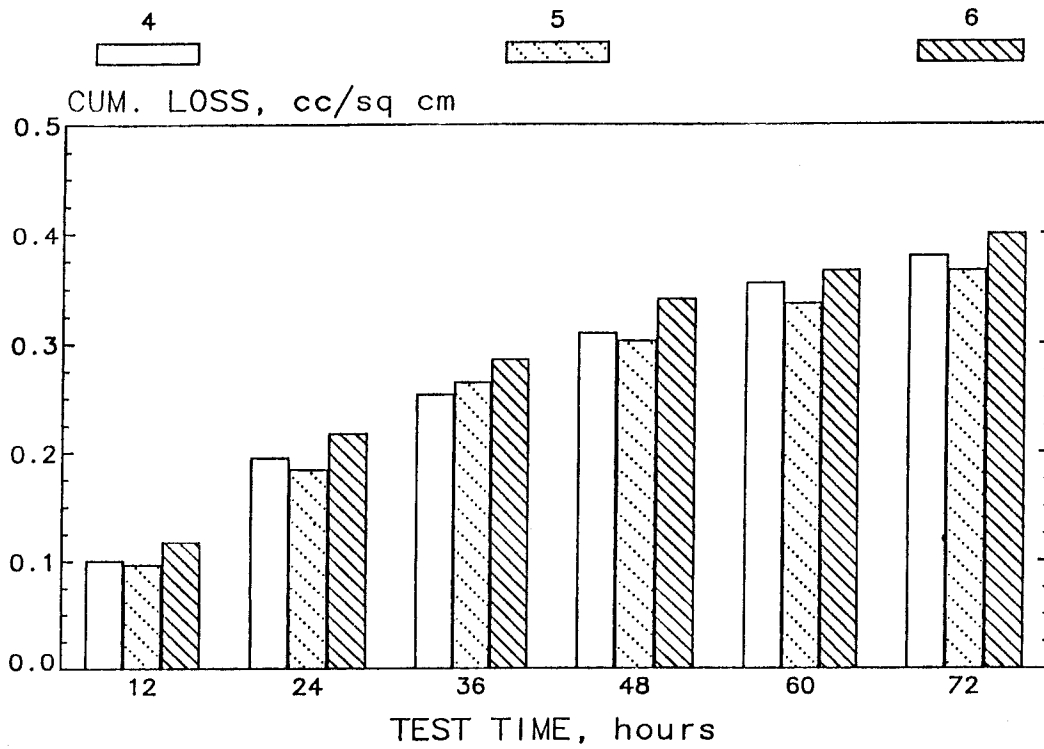


Figure 26. Abrasion-erosion data of mixtures no. 73 with melamine HRWR and W/C = 0.36

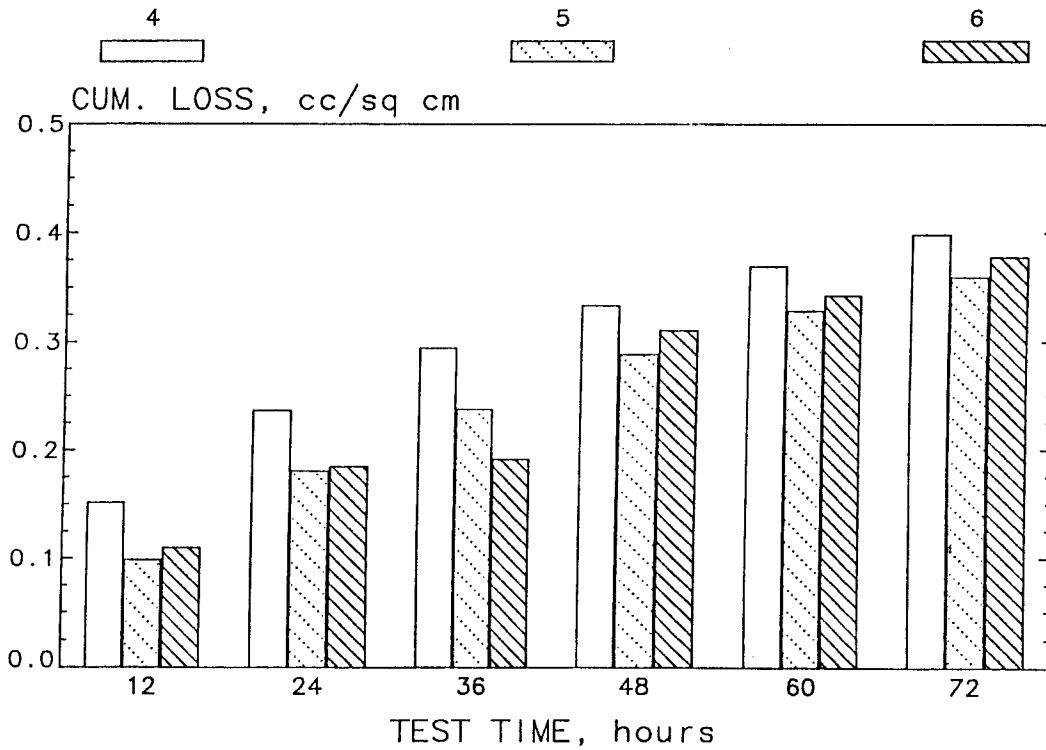


Figure 27. Abrasion-erosion data of mixtures no. 74 with melamine HRWR and W/C = 0.36

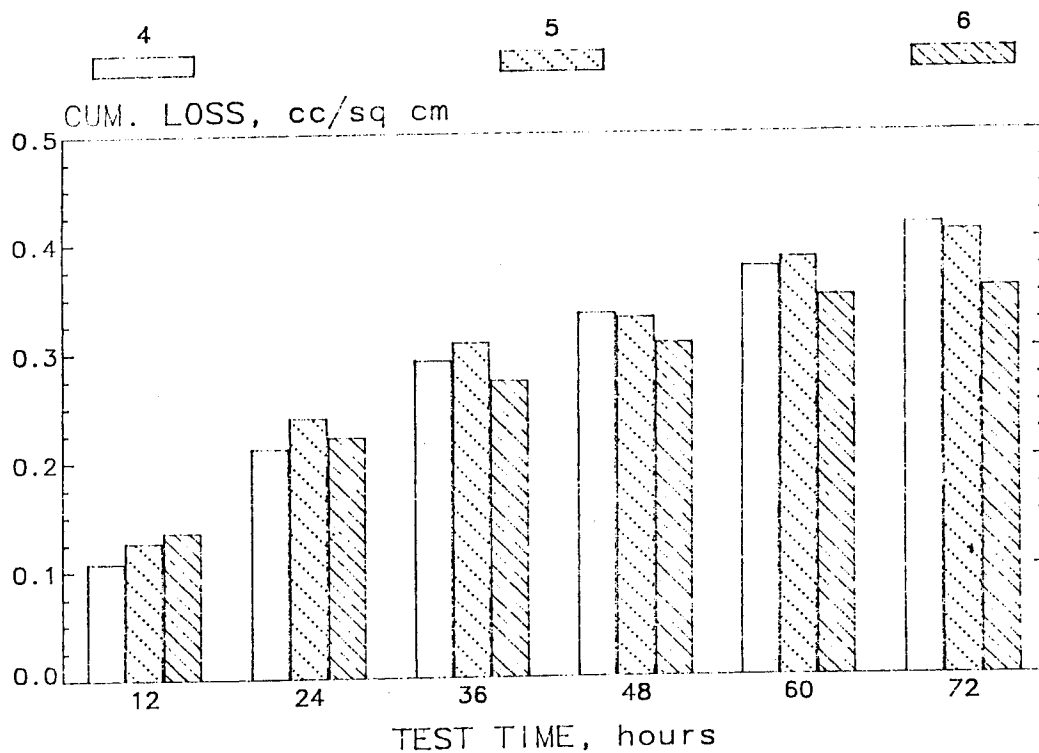


Figure 28. Abrasion-erosion data of mixtures no. 75 with melamine HRWR and W/C = 0.36

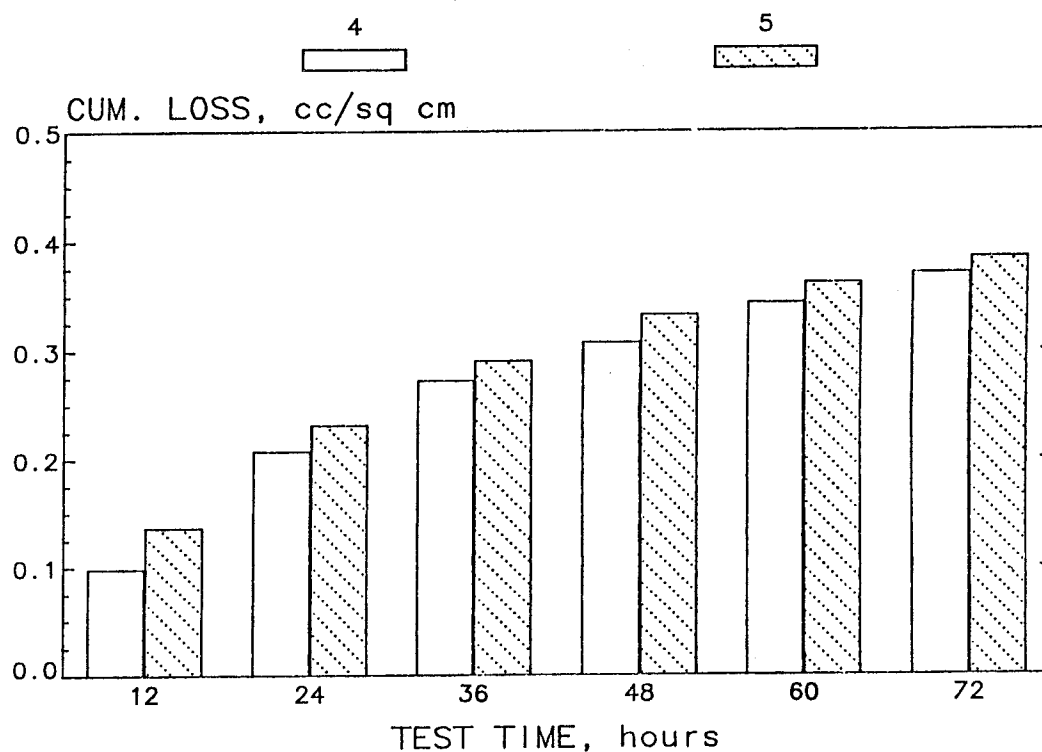


Figure 29. Abrasion-erosion data of mixtures no. 86 with melamine HRWR and W/C = 0.36

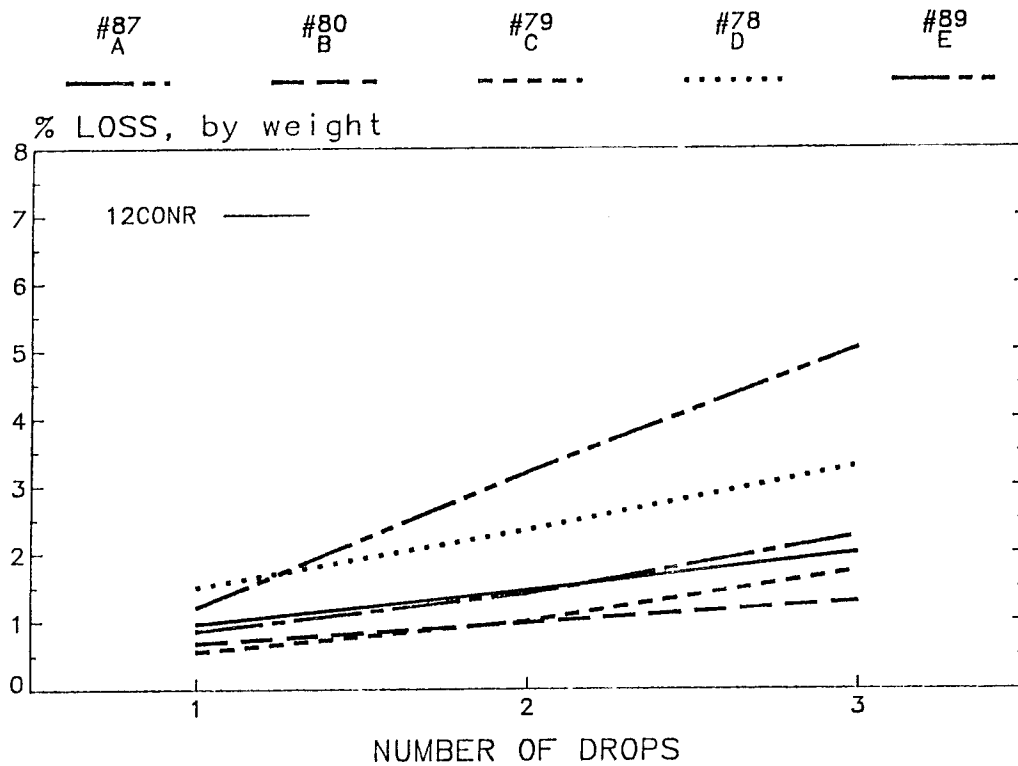


Figure 30. Washout data of mixtures with lignosulfonate HRWR and W/C = 0.36

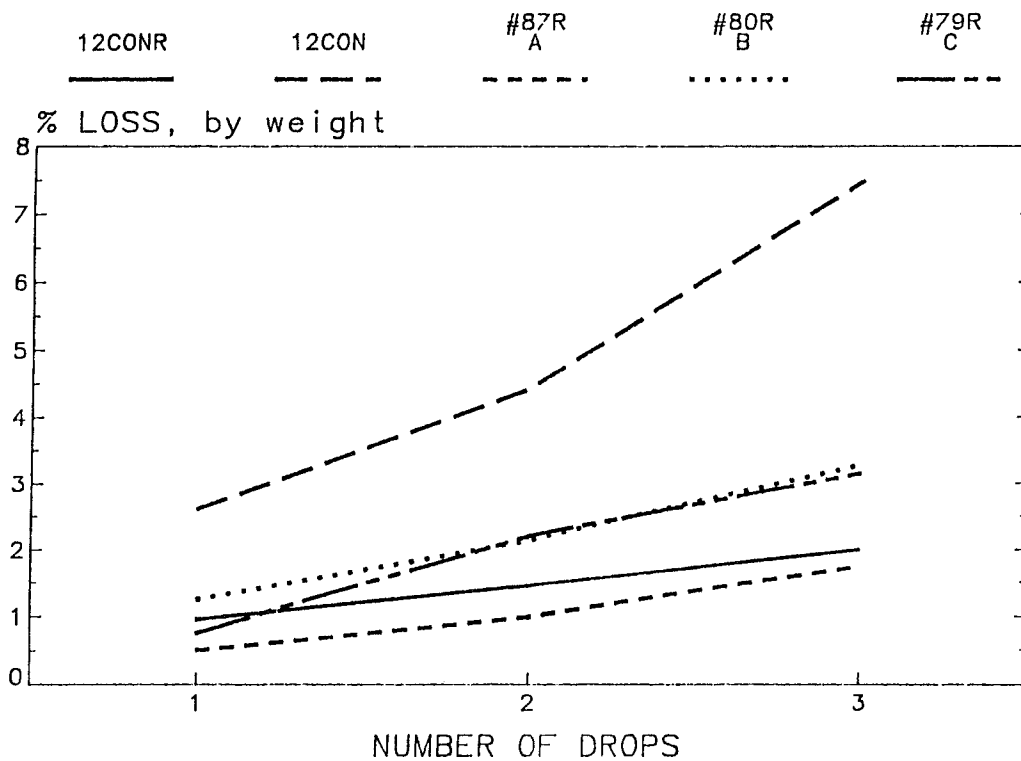


Figure 31. Washout data of mixtures with lignosulfonate HRWR and W/C = 0.36

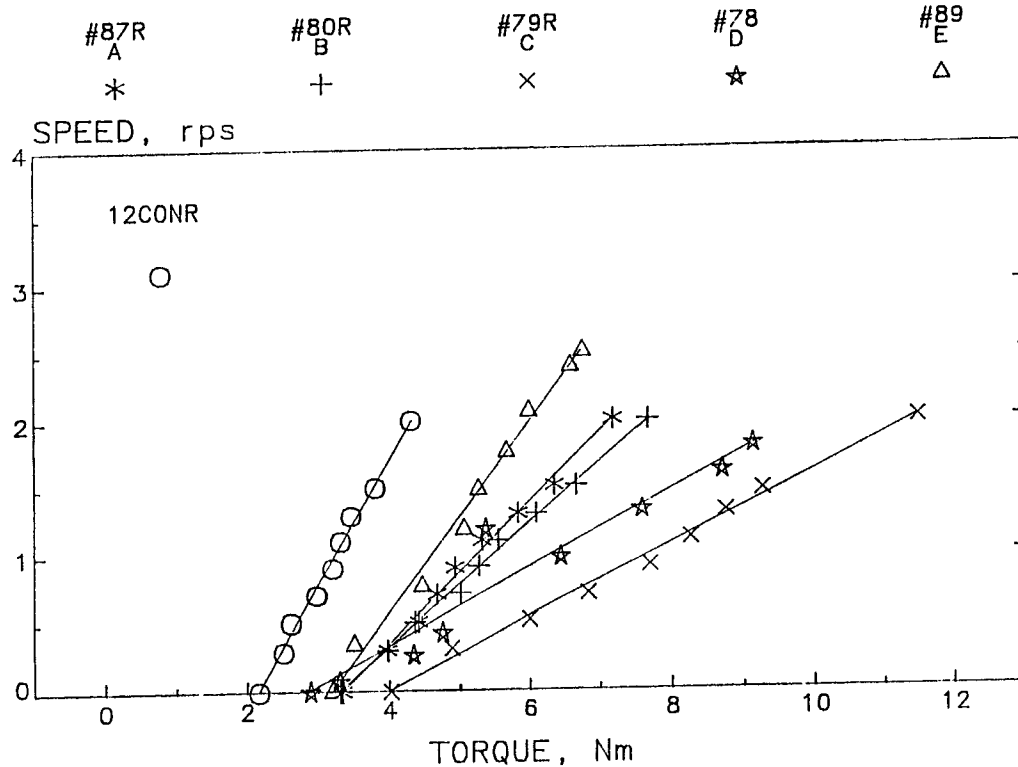


Figure 32. Two-point workability data of mixtures with lignosulfonate HRWR and W/C = 0.36

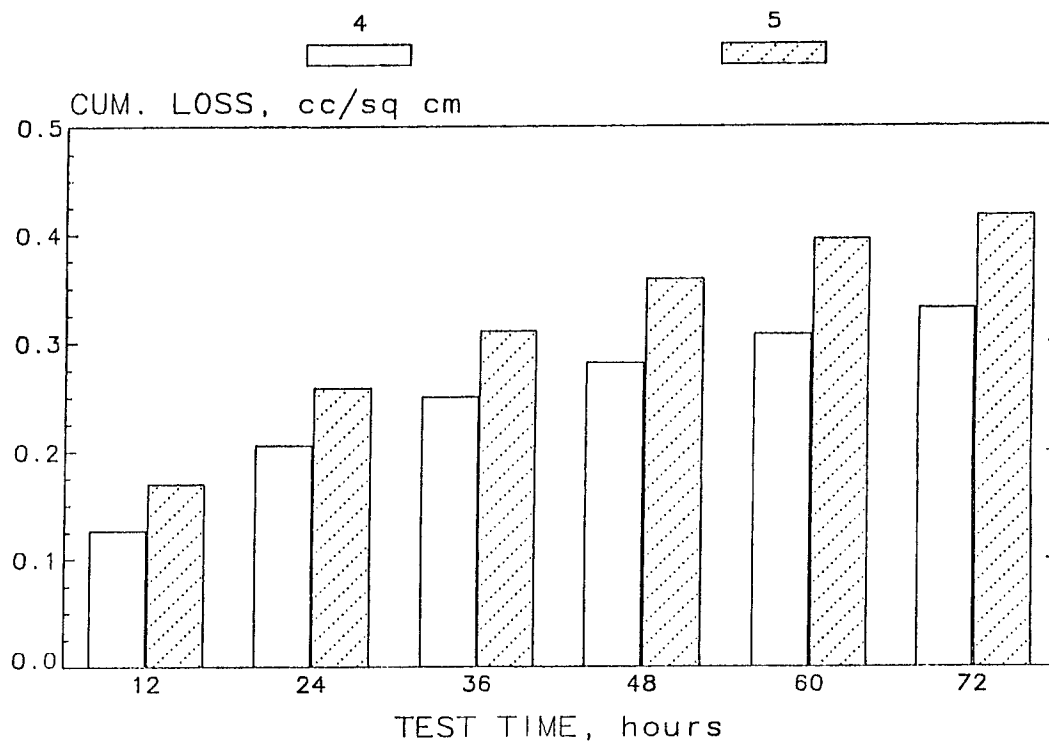


Figure 33. Abrasion-erosion data of mixtures no. 12CON with lignosulfonate HRWR and W/C = 0.36

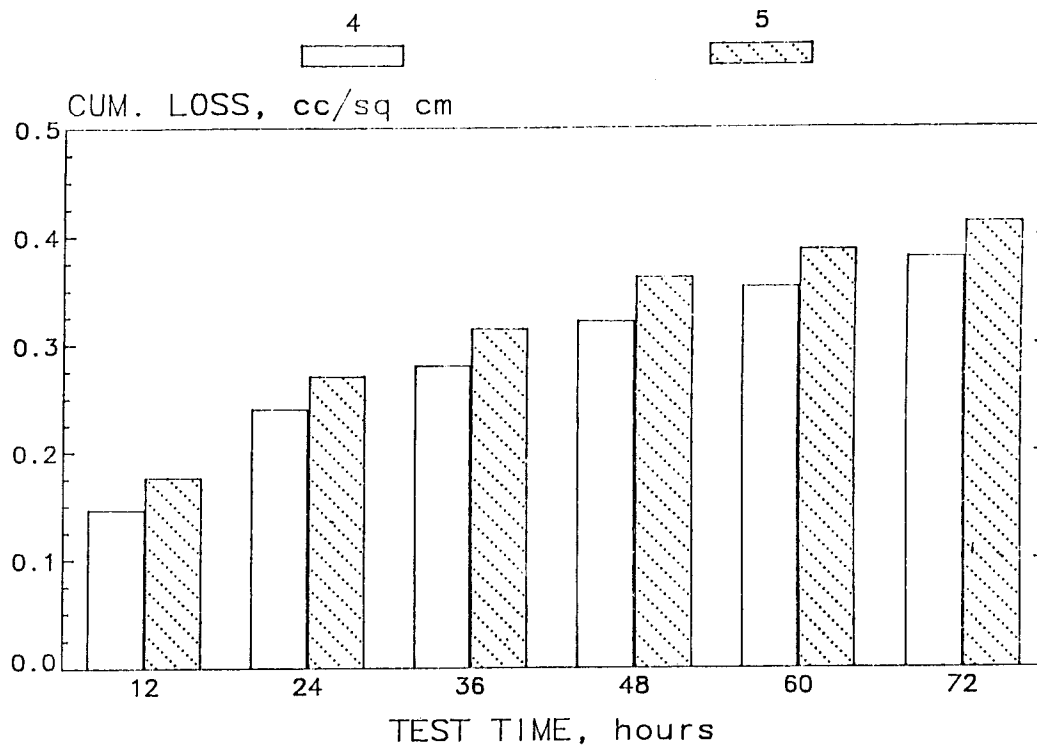


Figure 34. Abrasion-erosion data of mixtures no. 78 with lignosulfonate HRWR and W/C = 0.36

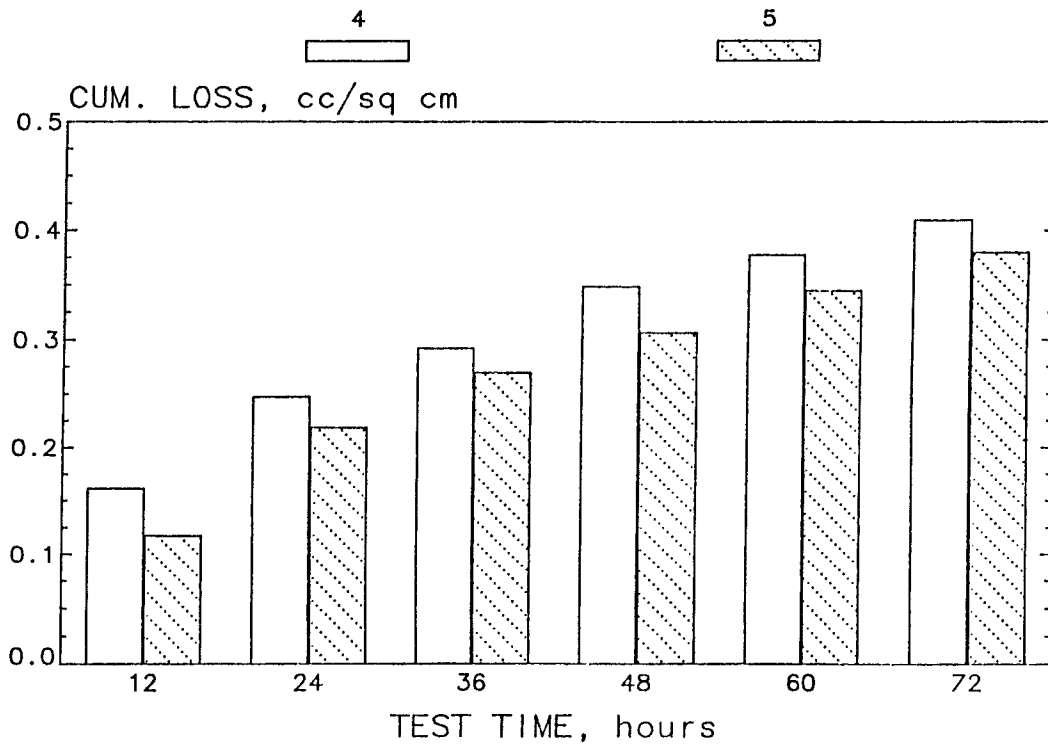


Figure 35. Abrasion-erosion data of mixtures no. 79 with lignosulfonate HRWR and W/C = 0.36

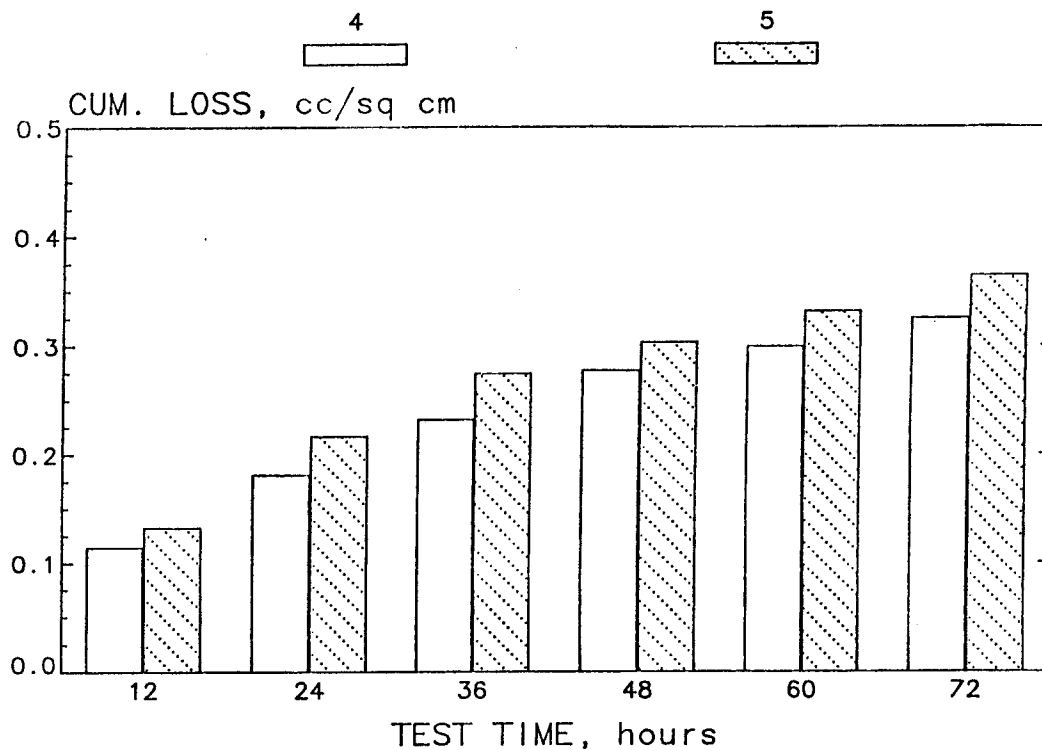


Figure 36. Abrasion-erosion data of mixtures no. 80 with lignosulfonate HRWR and W/C = 0.36

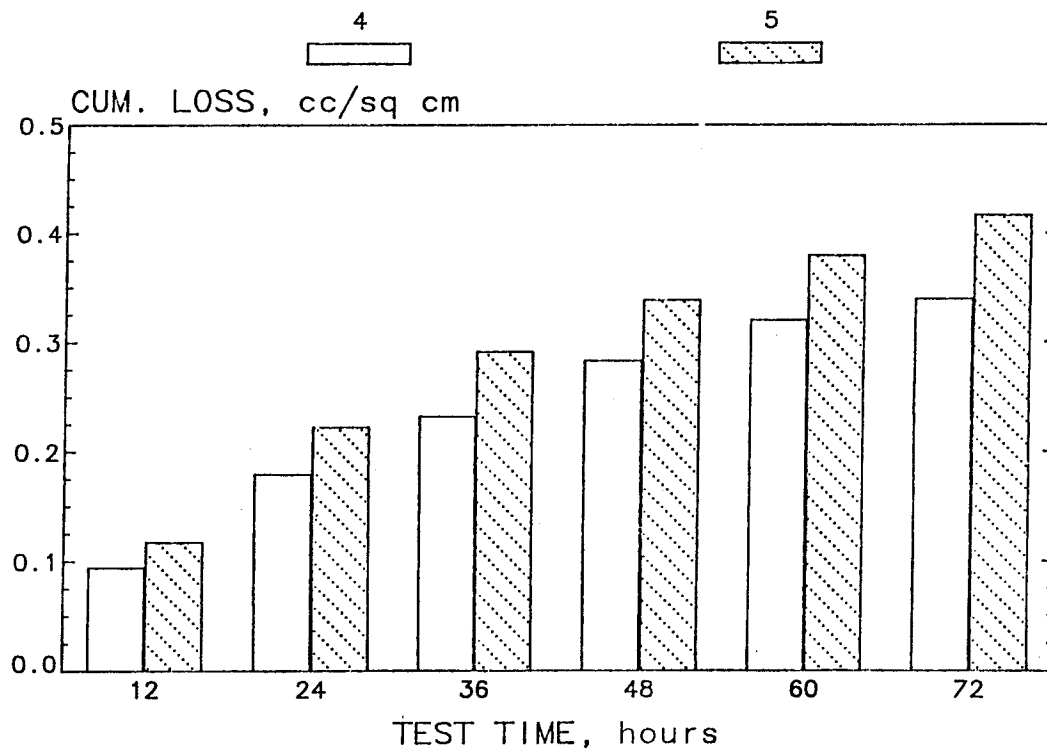


Figure 37. Abrasion-erosion data of mixtures no. 87 with lignosulfonate HRWR and W/C = 0.36

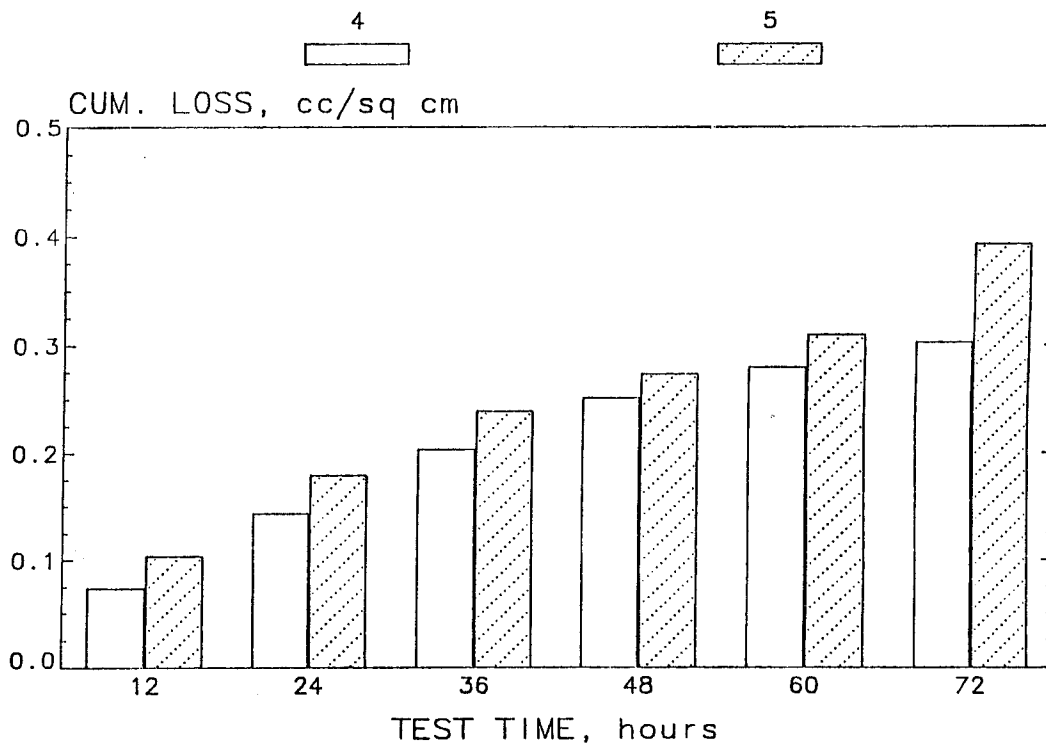


Figure 38. Abrasion-erosion data of mixtures no. 89 with lignosulfonate HRWR and W/C = 0.36

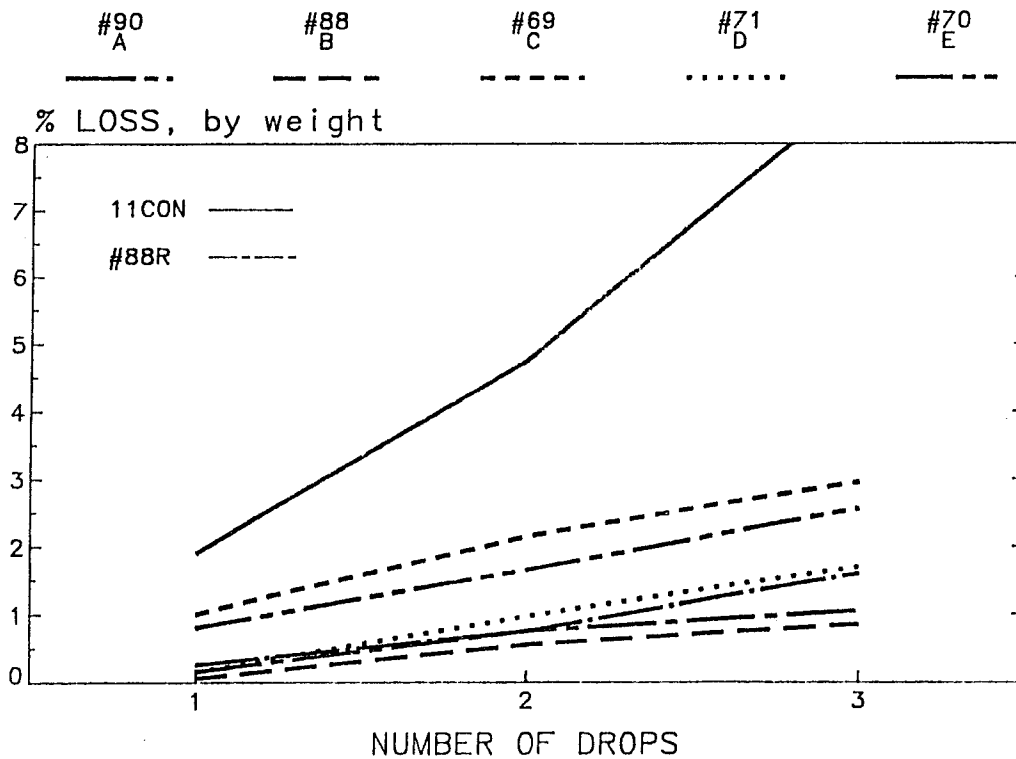


Figure 39. Washout data of mixtures with lignosulfonate HRWR and W/C = 0.32

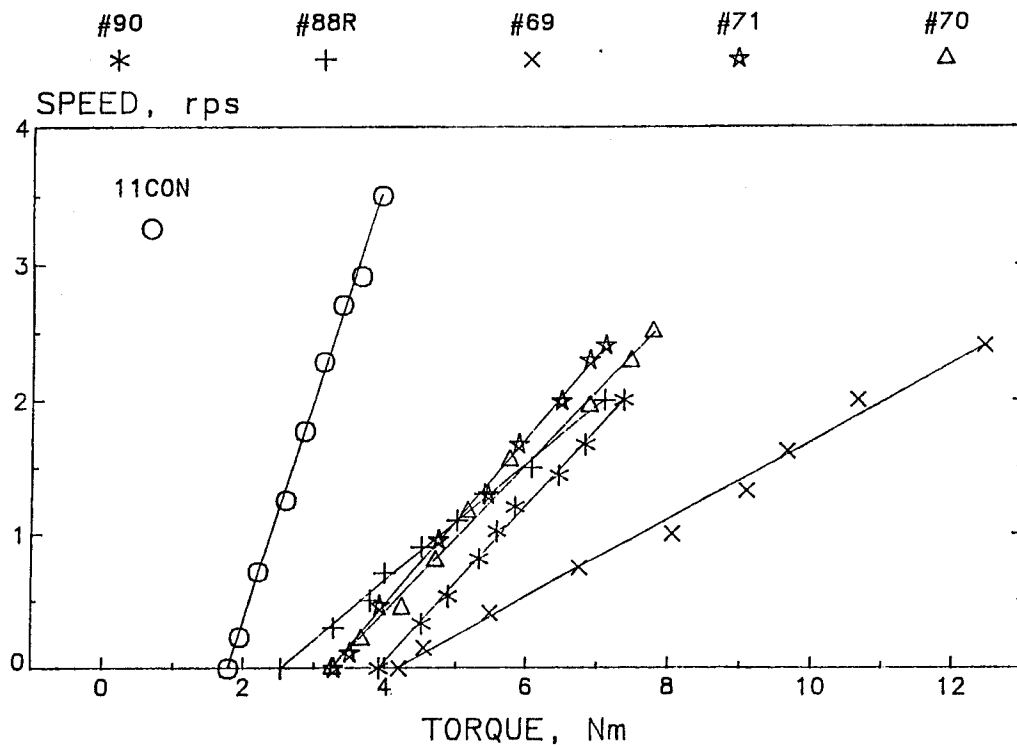


Figure 40. Two-point workability data of mixtures with lignosulfonate
HRWR and W/C = 0.32

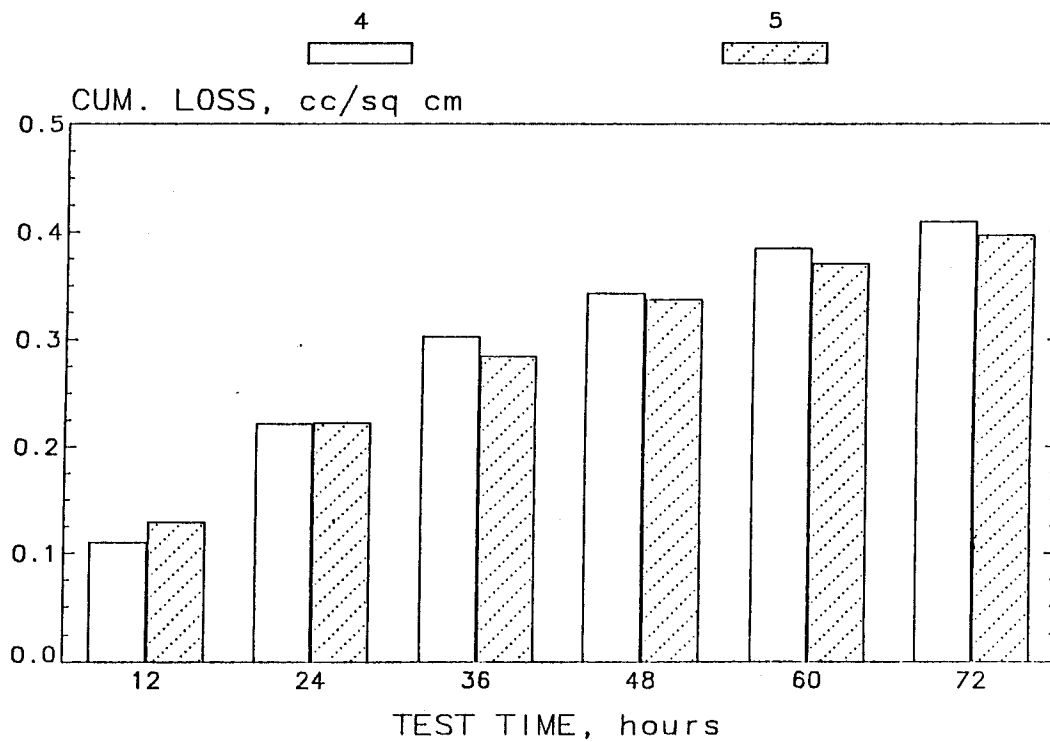


Figure 41. Abrasion-erosion data of mixtures no. 88 with lignosulfonate
HRWR and W/C = 0.32

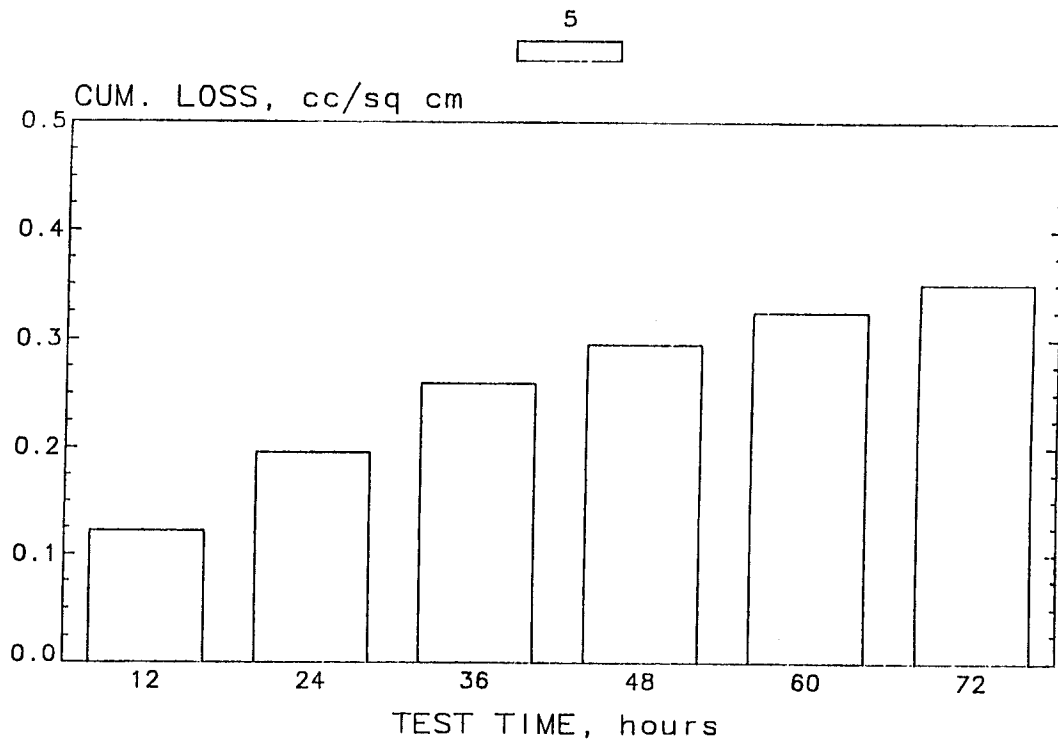


Figure 42. Abrasion-erosion data of mixtures no. 90 with lignosulfonate HRWR and W/C = 0.32

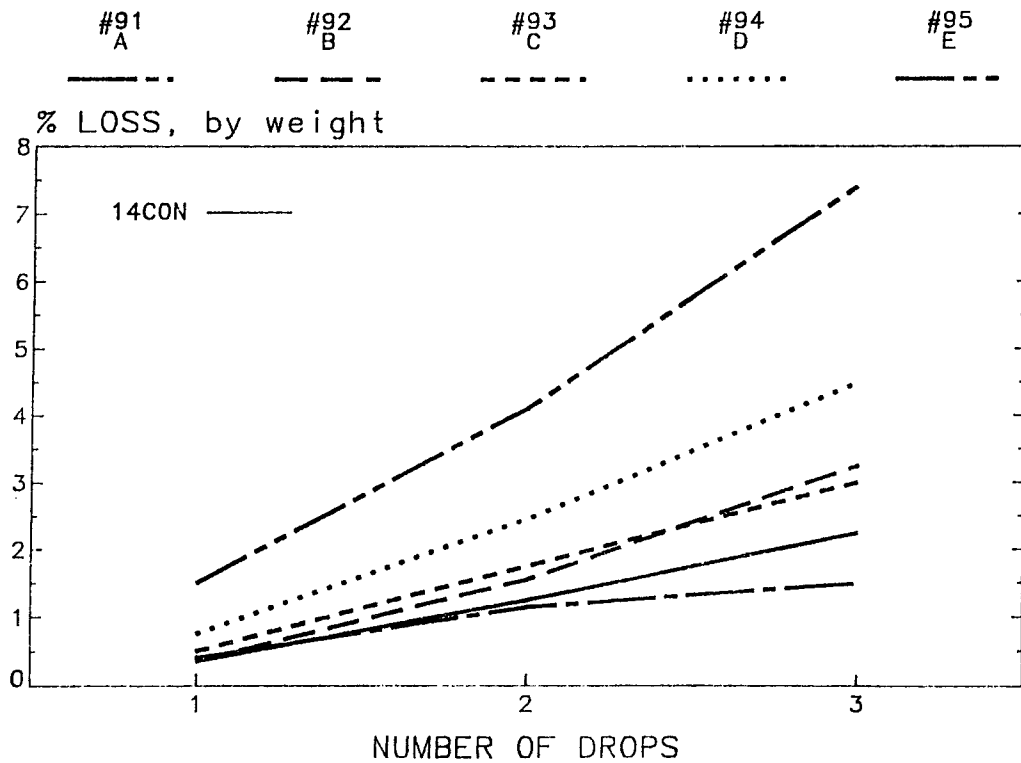


Figure 43. Washout data of mixtures with lignosulfonate HRWR and W/C = 0.40

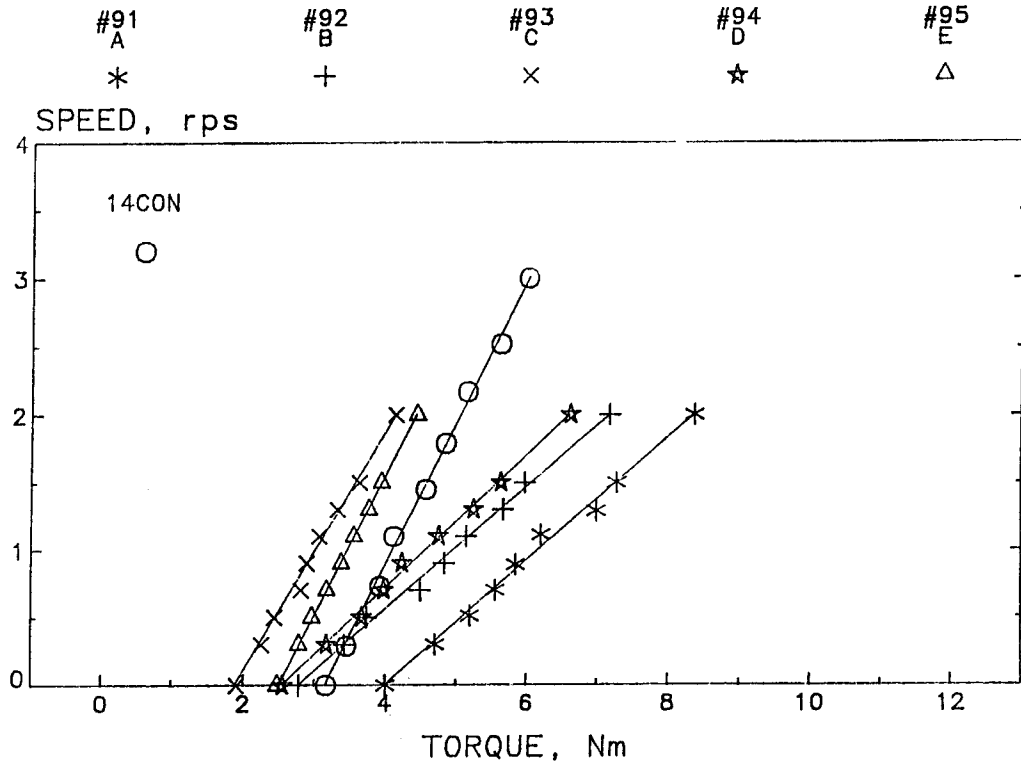


Figure 44. Two-point workability data of mixtures with lignosulfonate
HRWR and W/C = 0.40

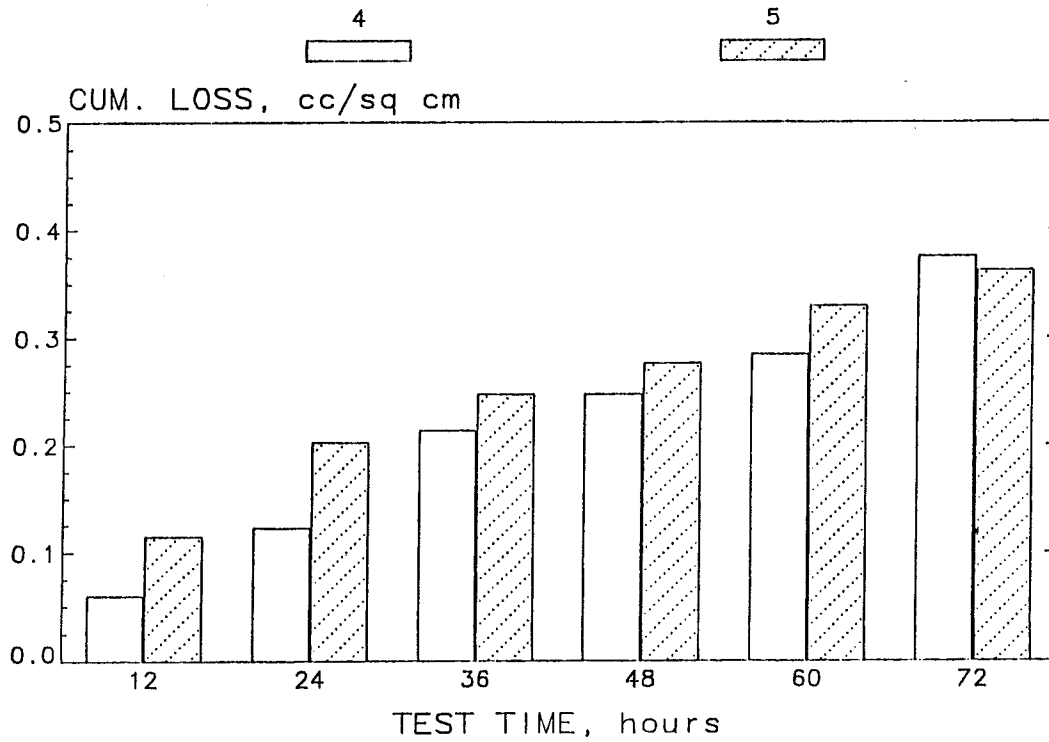


Figure 45. Abrasion-erosion data of mixtures no. 14CON with
lignosulfonate HRWR and W/C = 0.40

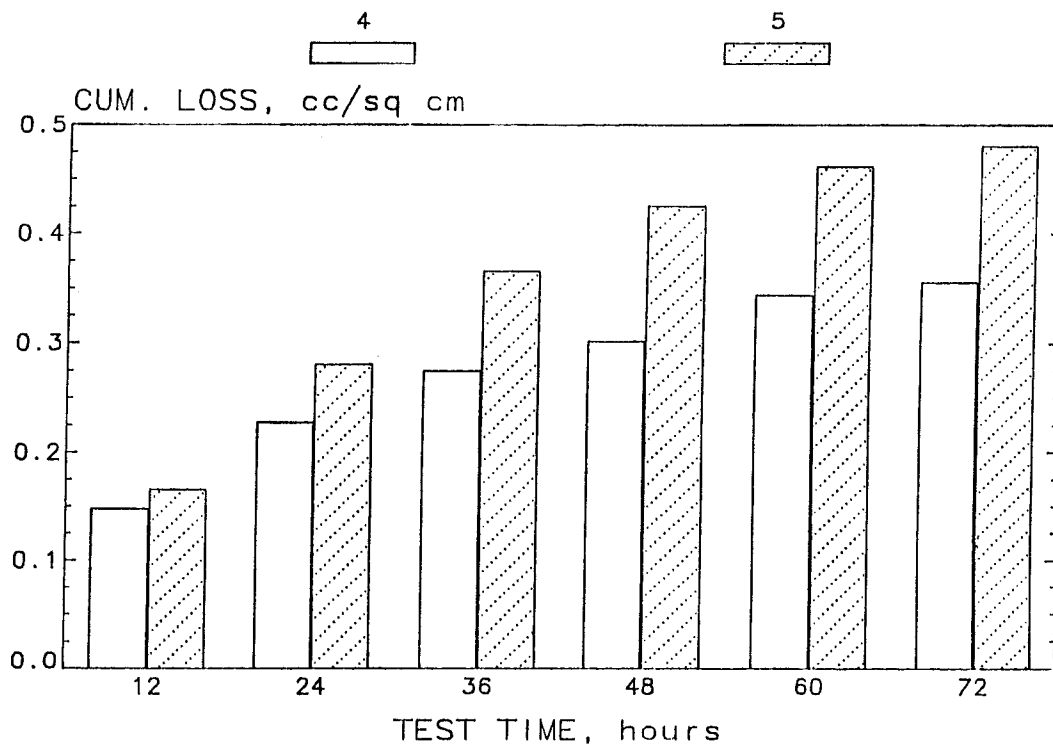


Figure 46. Abrasion-erosion data of mixtures no. 91 with lignosulfonate HRWR and W/C = 0.40

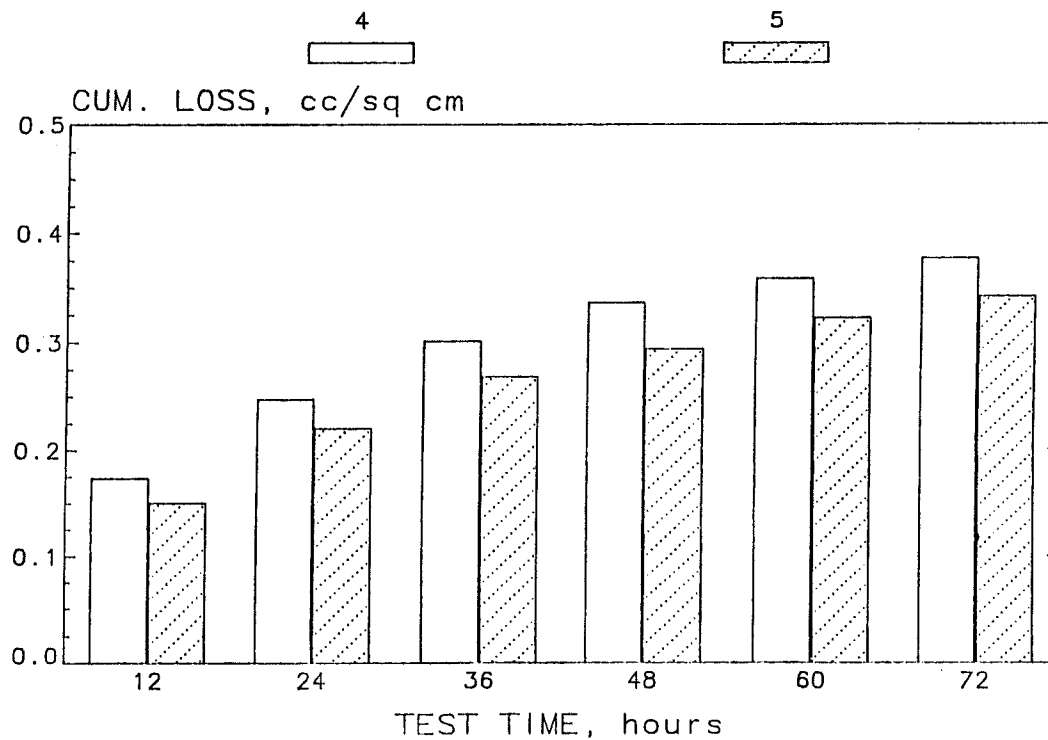


Figure 47. Abrasion-erosion data of mixtures no. 92 with lignosulfonate HRWR and W/C = 0.40

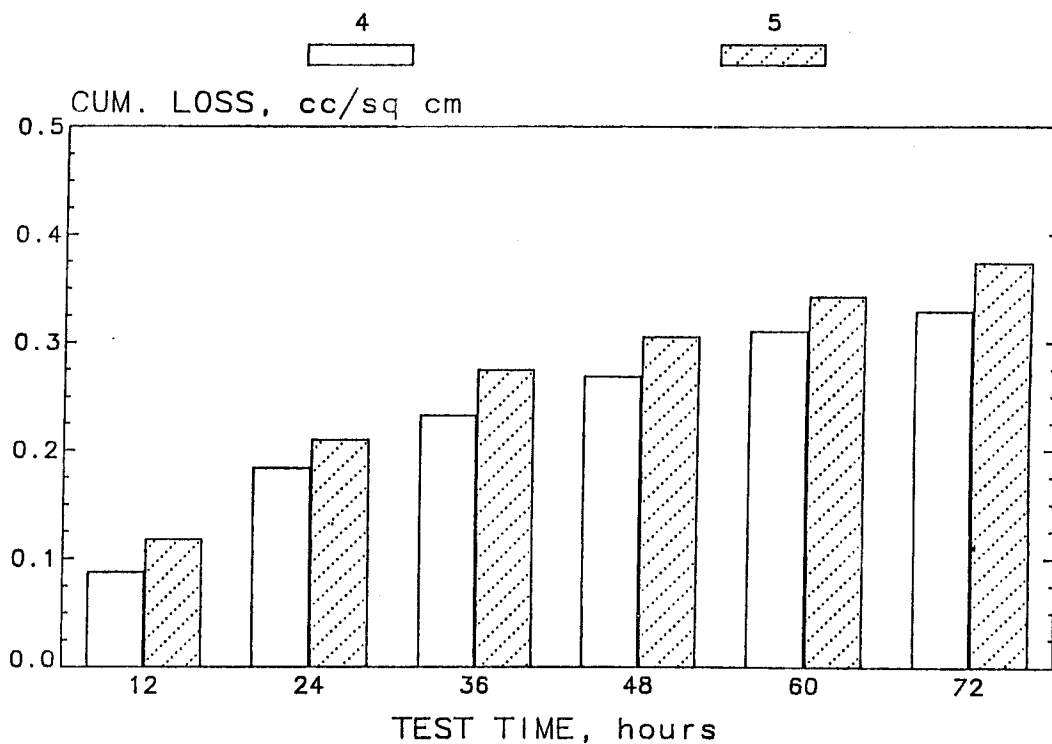


Figure 48. Abrasion-erosion data of mixtures no. 93 with lignosulfonate
HRWR and W/C = 0.40

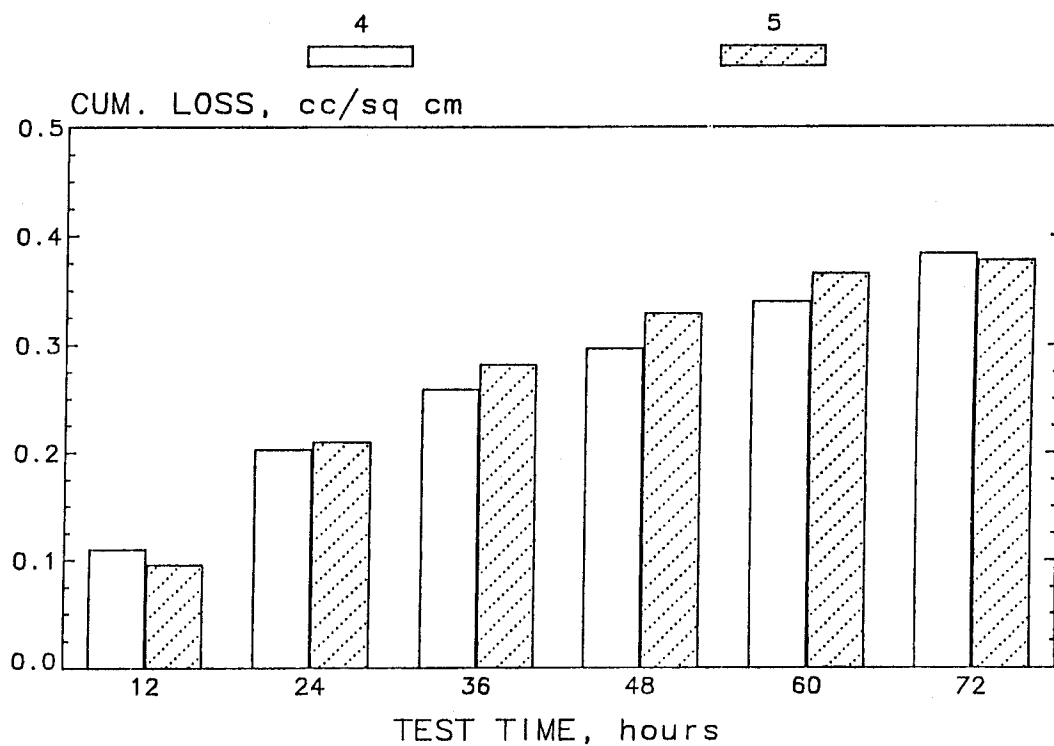


Figure 49. Abrasion-erosion data of mixtures no. 94 with lignosulfonate
HRWR and W/C = 0.40

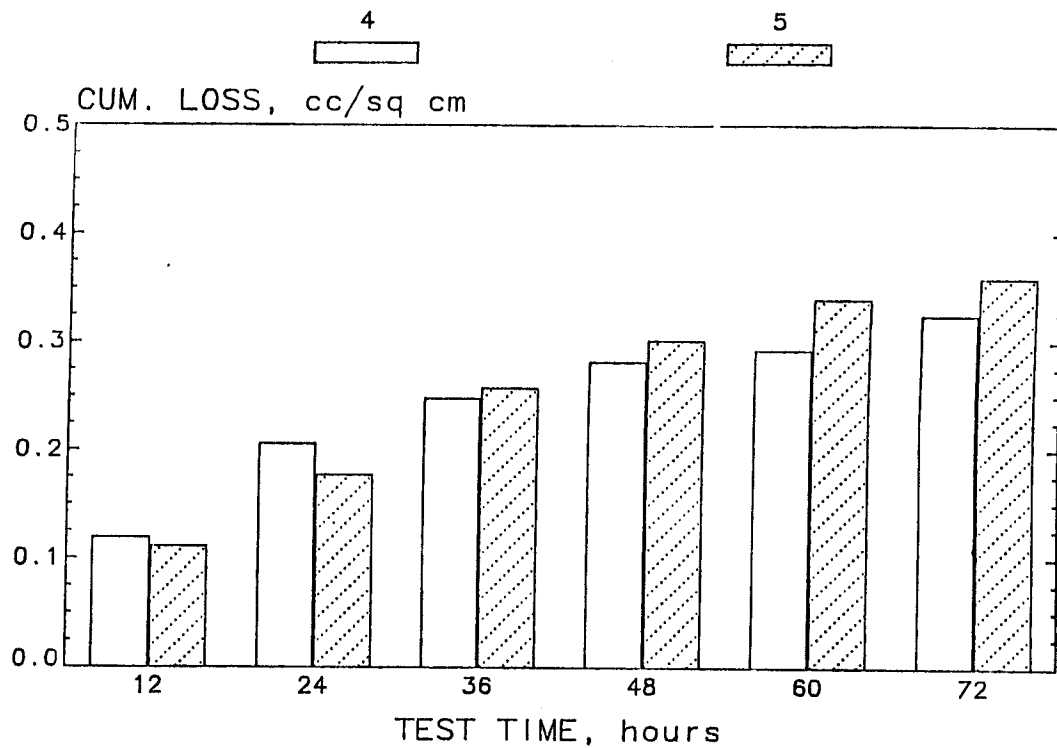


Figure 50. Abrasion-erosion data of mixtures no. 95 with lignosulfonate HRWR and W/C = 0.40

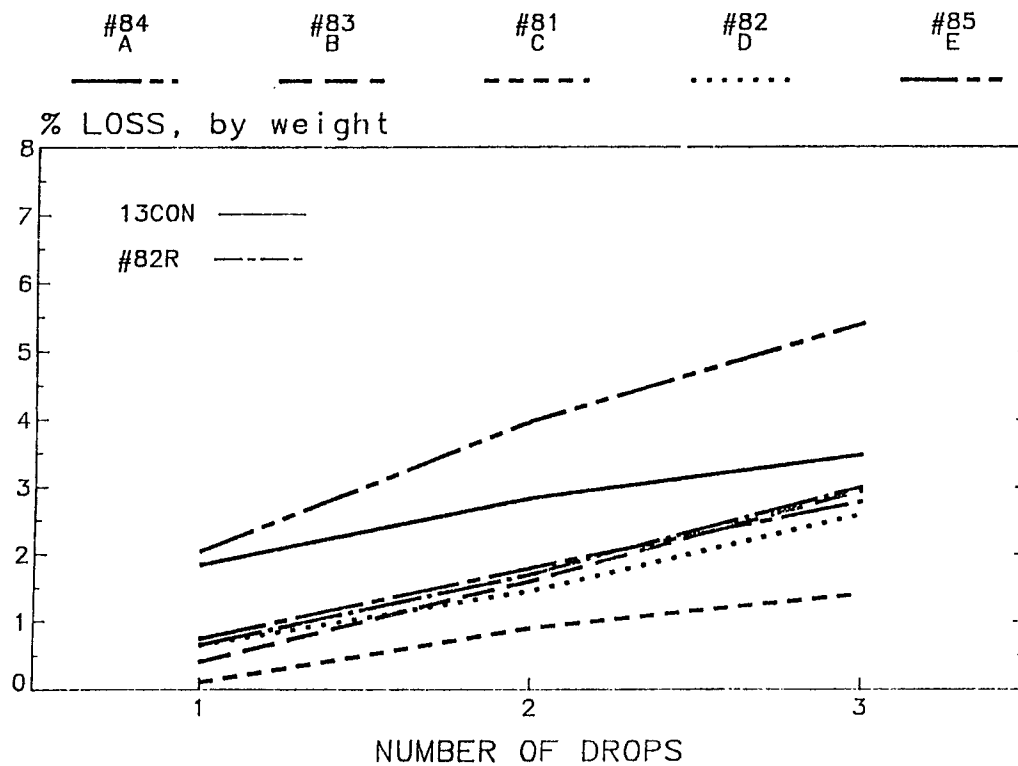


Figure 51. Washout data of mixtures with lignosulfonate HRWR and W/C = 0.42

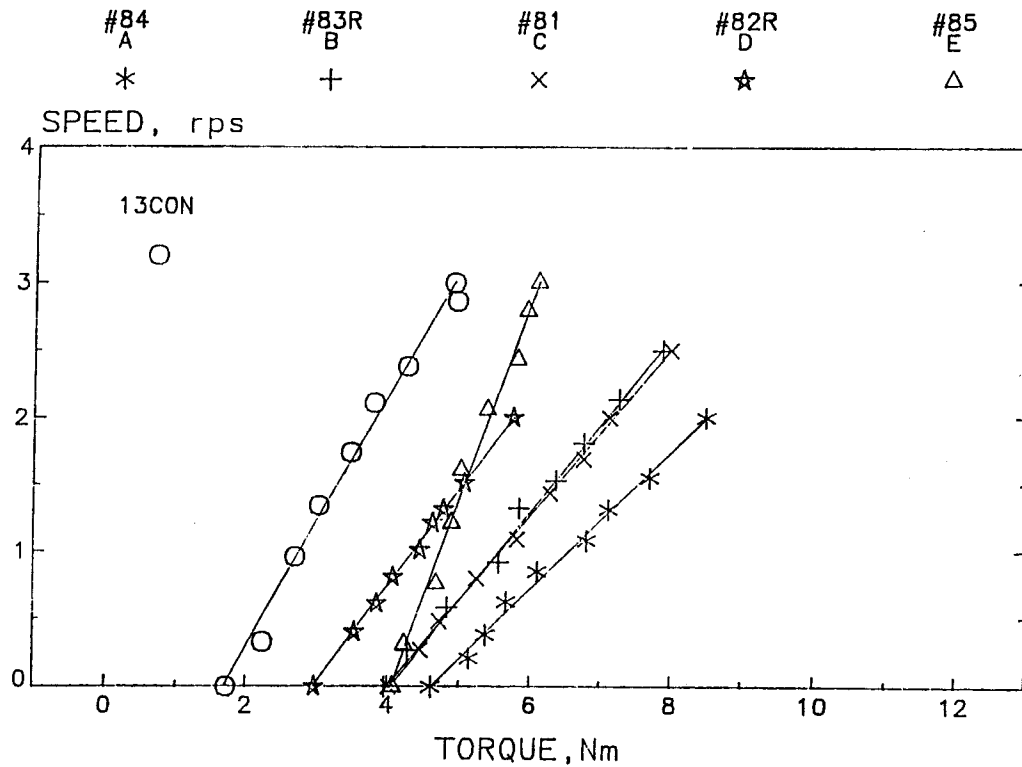


Figure 52. Two-point workability data of mixtures with lignosulfonate
HRWR and W/C = 0.42

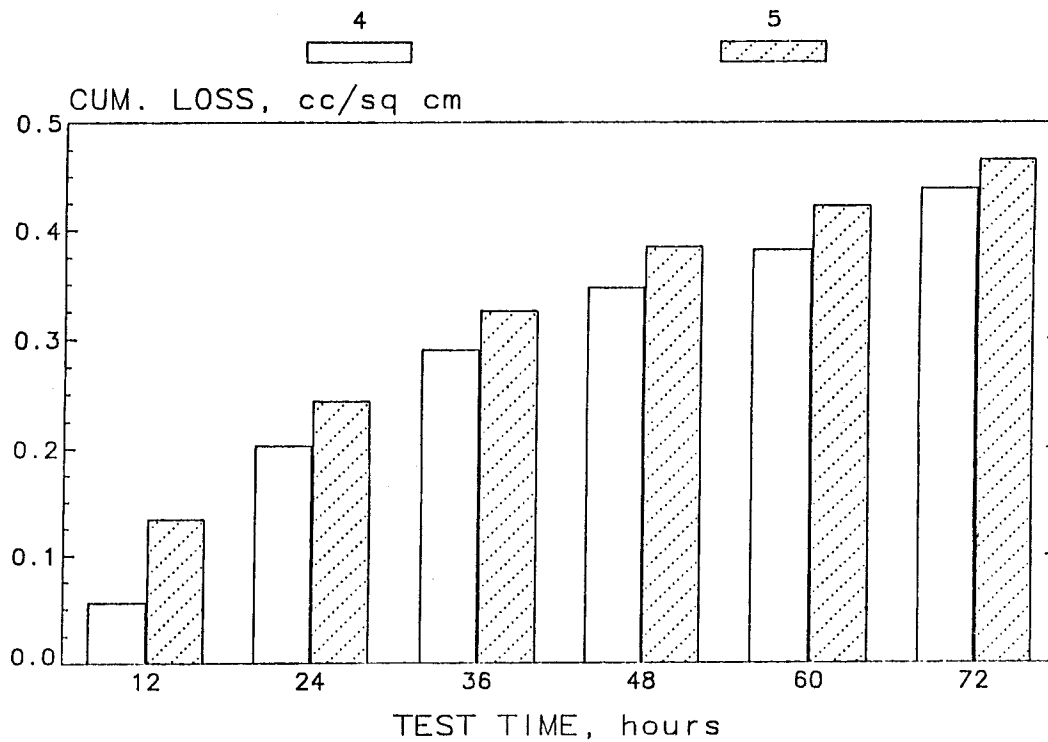


Figure 53. Abrasion-erosion data of mixtures no. 13CON with
lignosulfonate HRWR and W/C = 0.42

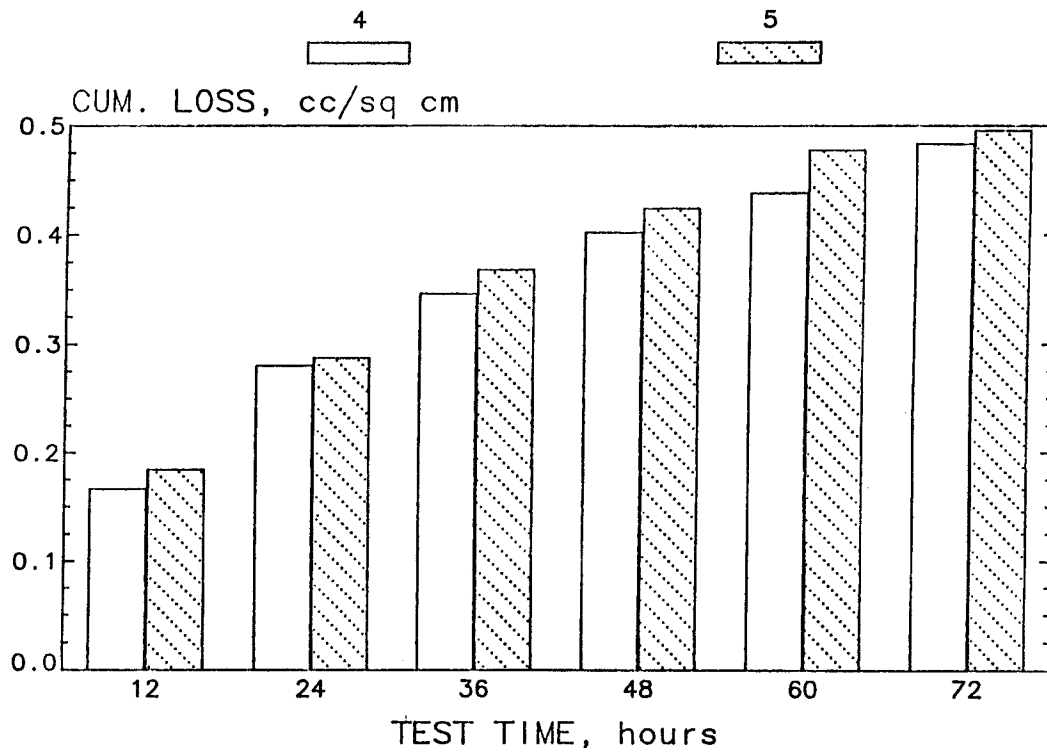


Figure 54. Abrasion-erosion data of mixtures no. 81 with lignosulfonate HRWR and W/C = 0.42

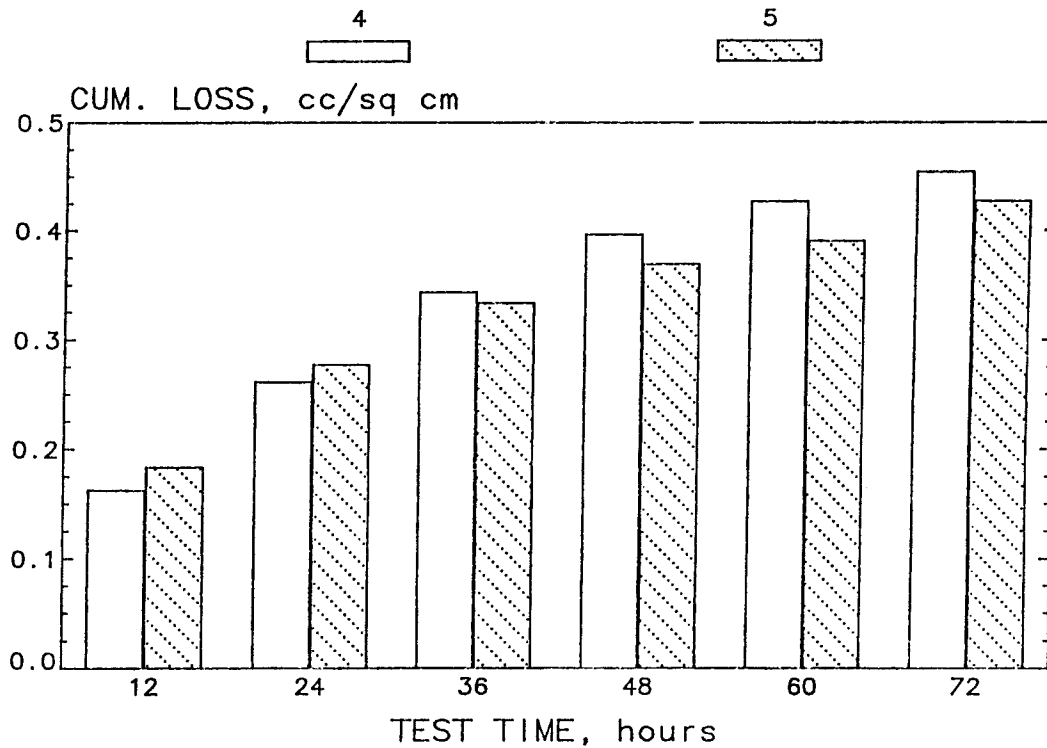


Figure 55. Abrasion-erosion data of mixtures no. 82 with lignosulfonate HRWR and W/C = 0.42

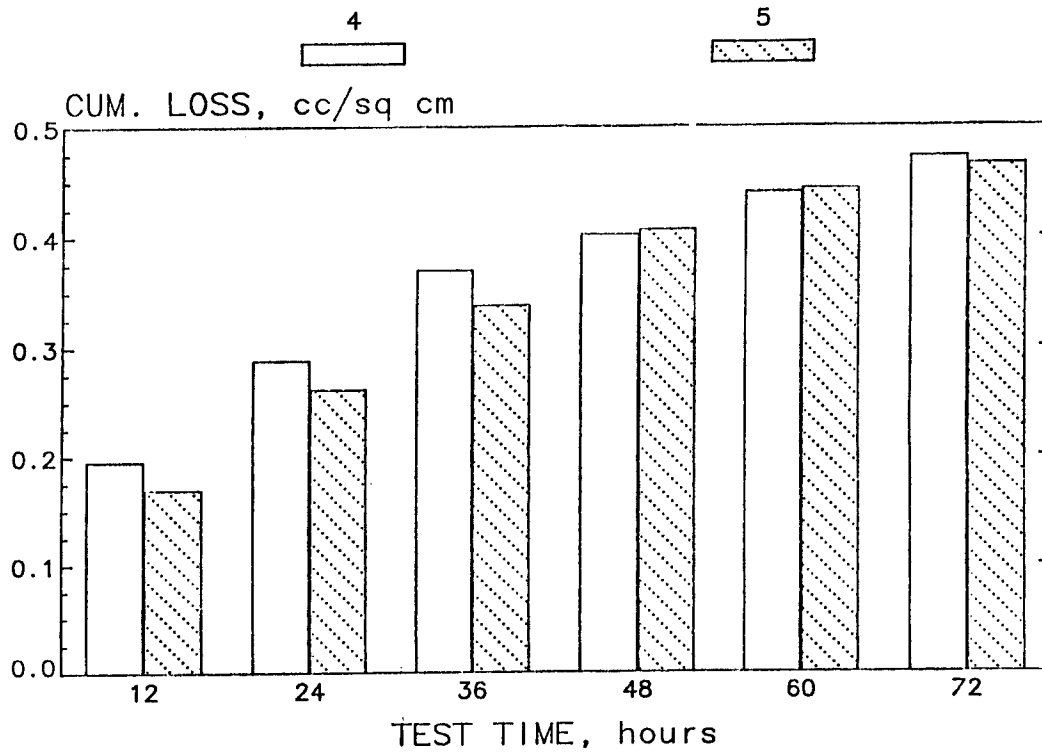


Figure 56. Abrasion-erosion data of mixtures no. 83 with lignosulfonate
HRWR and W/C = 0.42

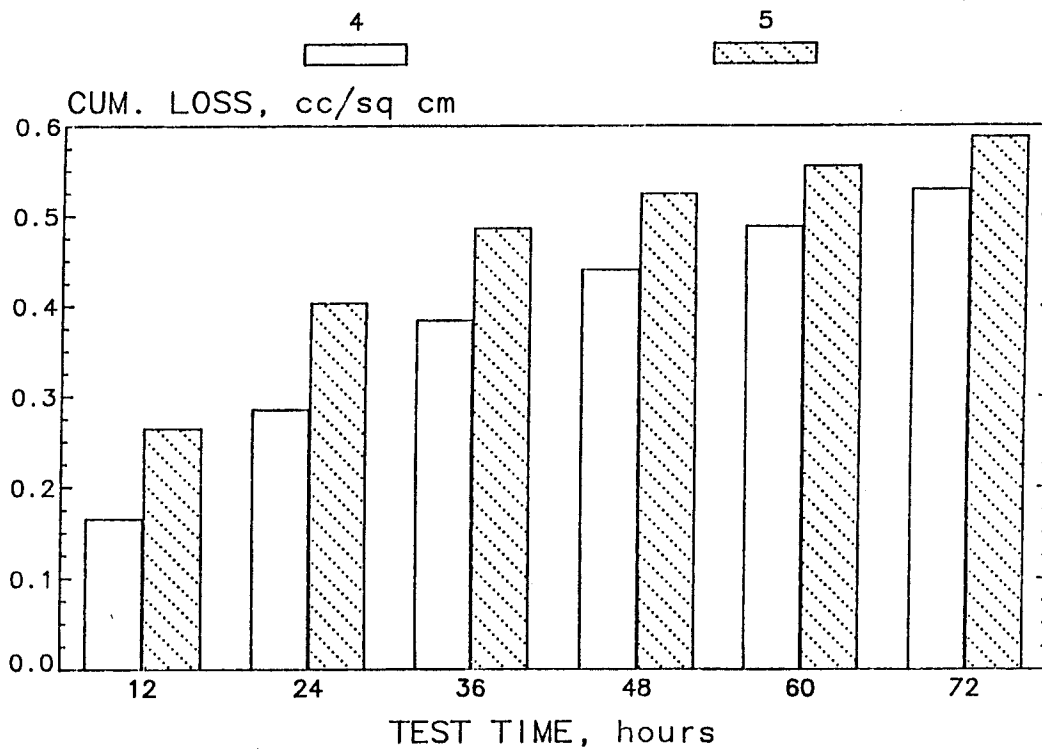


Figure 57. Abrasion-erosion data of mixtures no. 84 with lignosulfonate
HRWR and W/C = 0.42

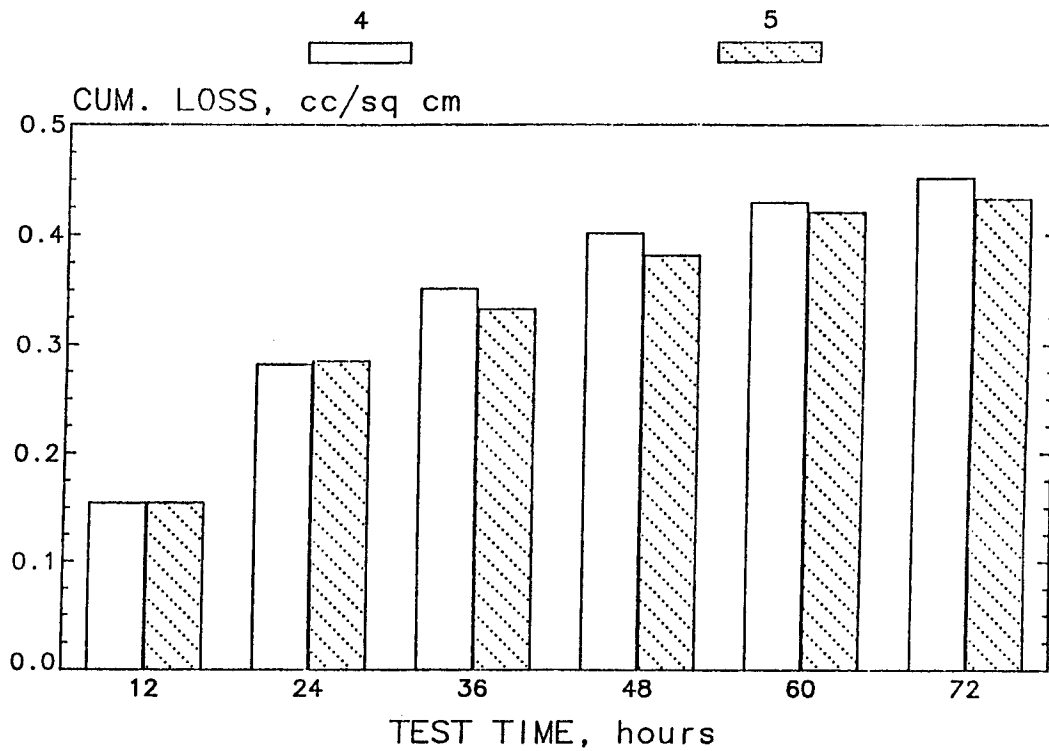


Figure 58. Abrasion-erosion data of mixtures no. 85 with lignosulfonate HRWR and W/C = 0.42

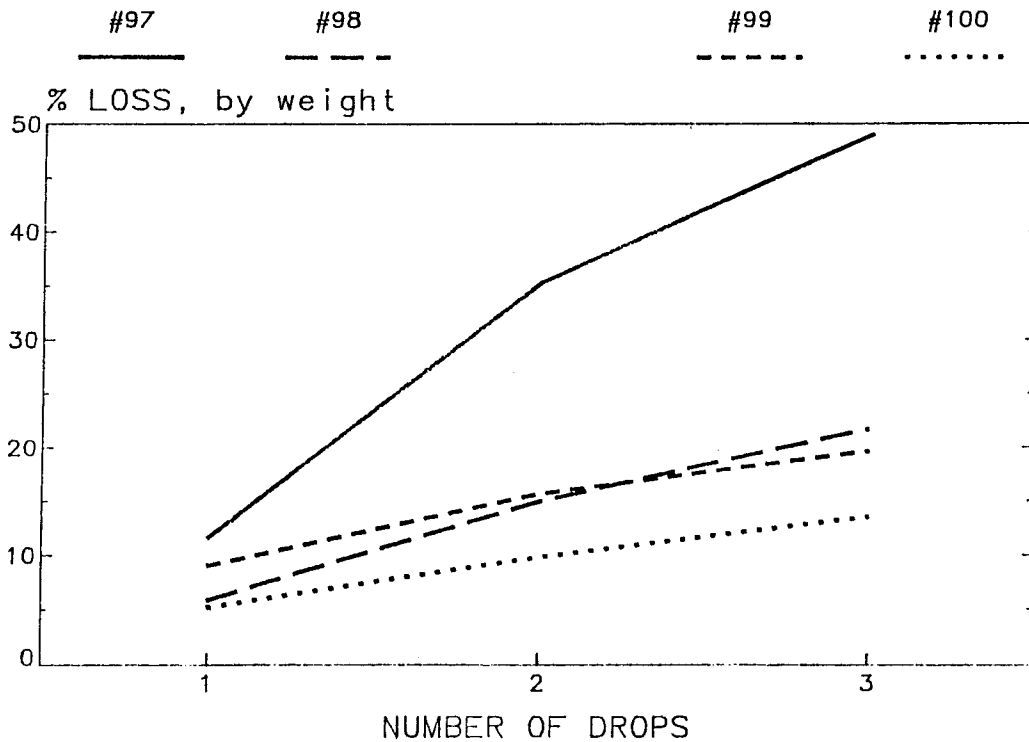


Figure 59. Washout data of conventional tremie concrete mixtures

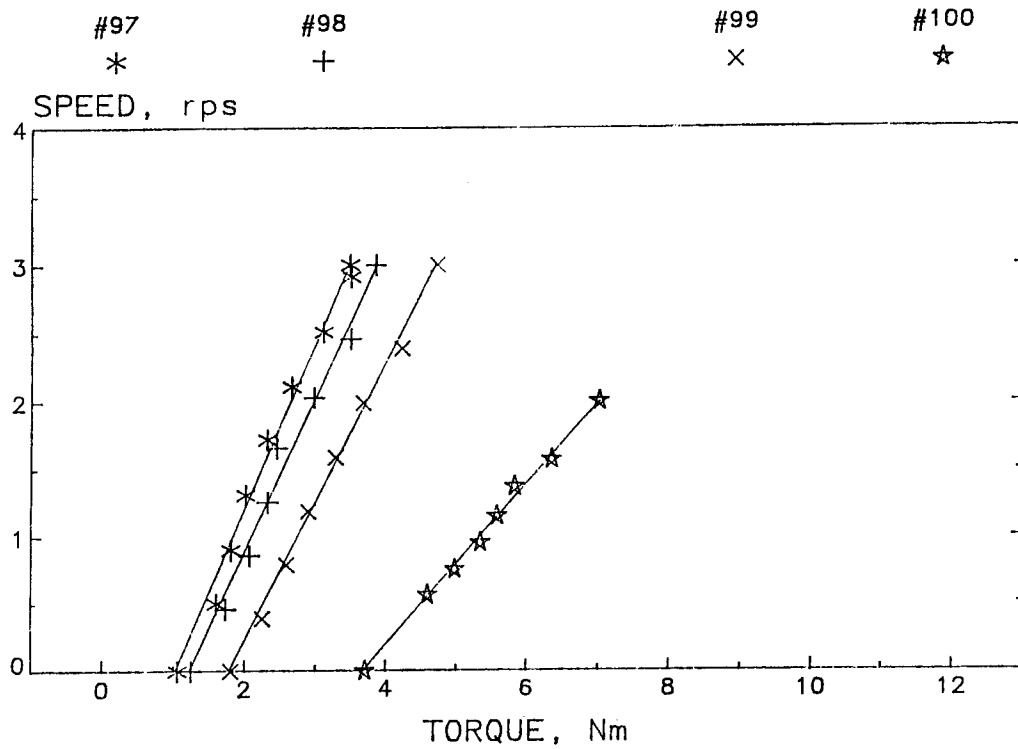


Figure 60. Two-point workability data of conventional tremie concrete mixtures

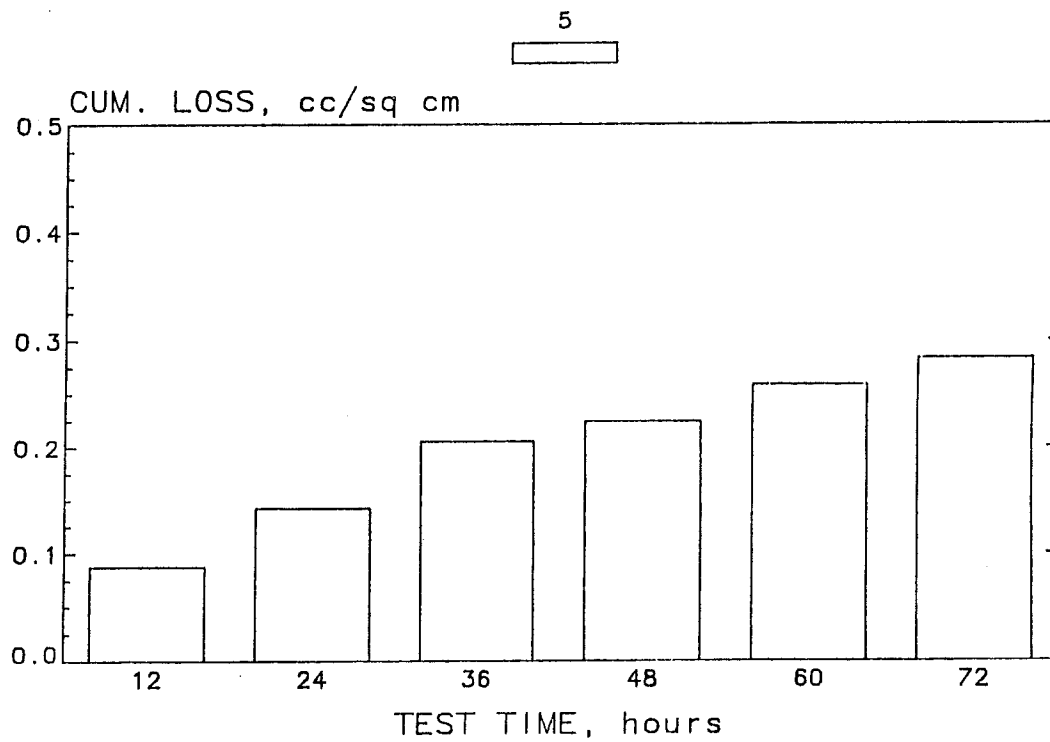


Figure 61. Abrasion-erosion data of conventional tremie concrete mixture no. 97

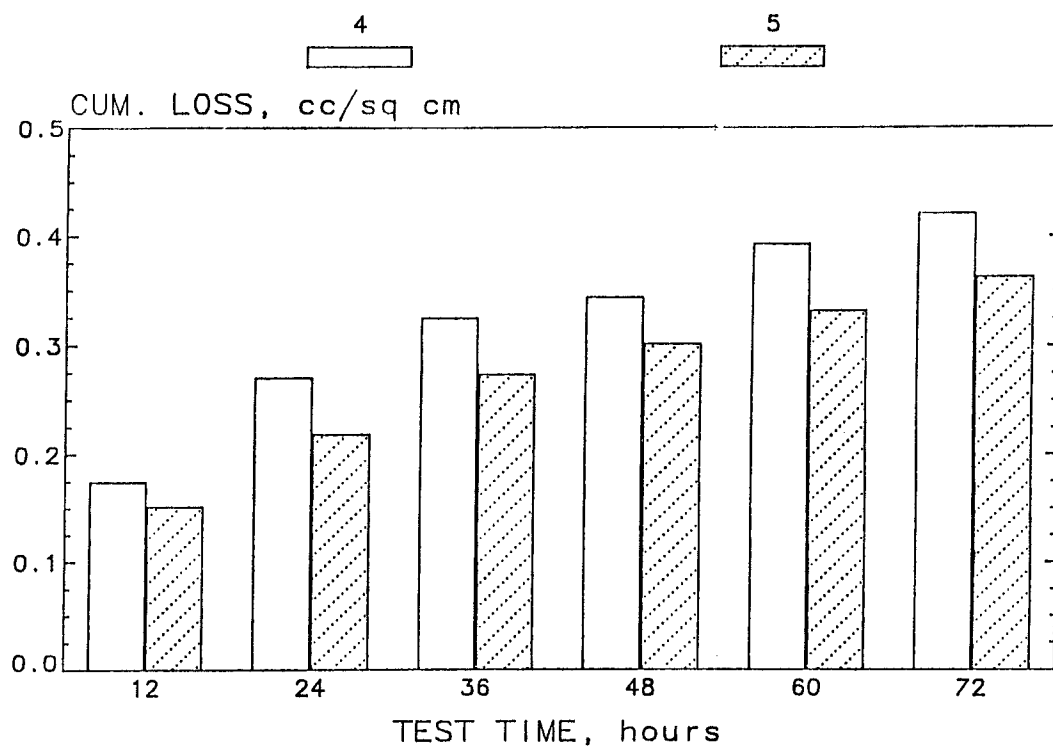


Figure 62. Abrasion-erosion data of conventional tremie concrete mixture no. 98

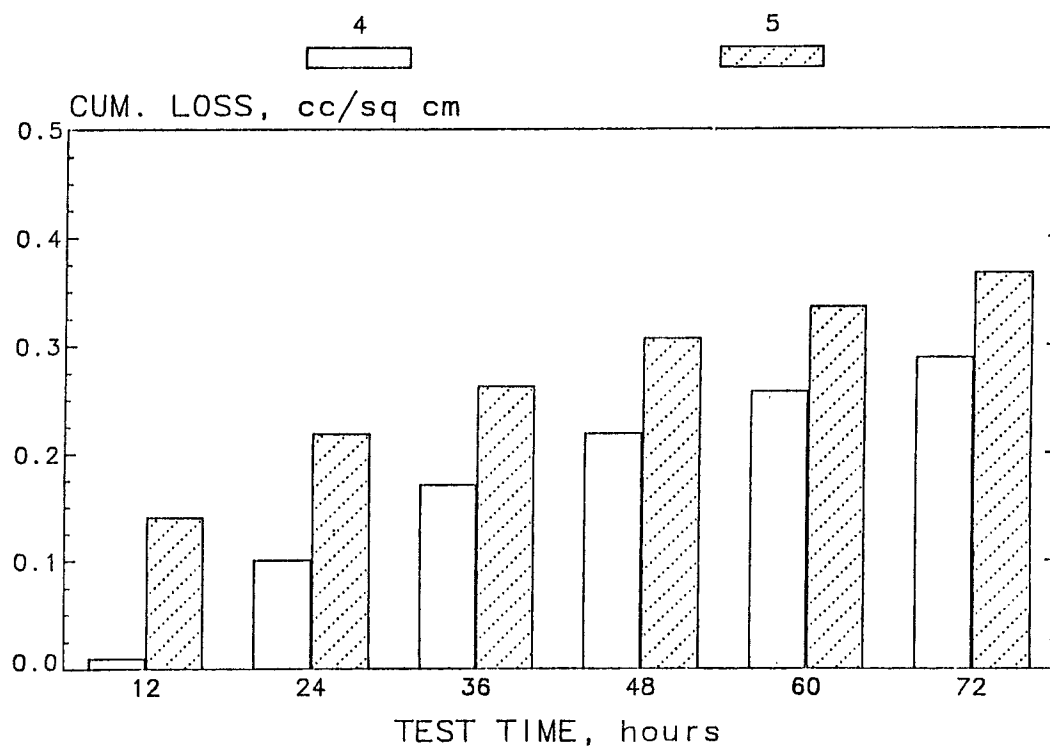


Figure 63. Abrasion-erosion data of conventional tremie concrete mixture no. 99

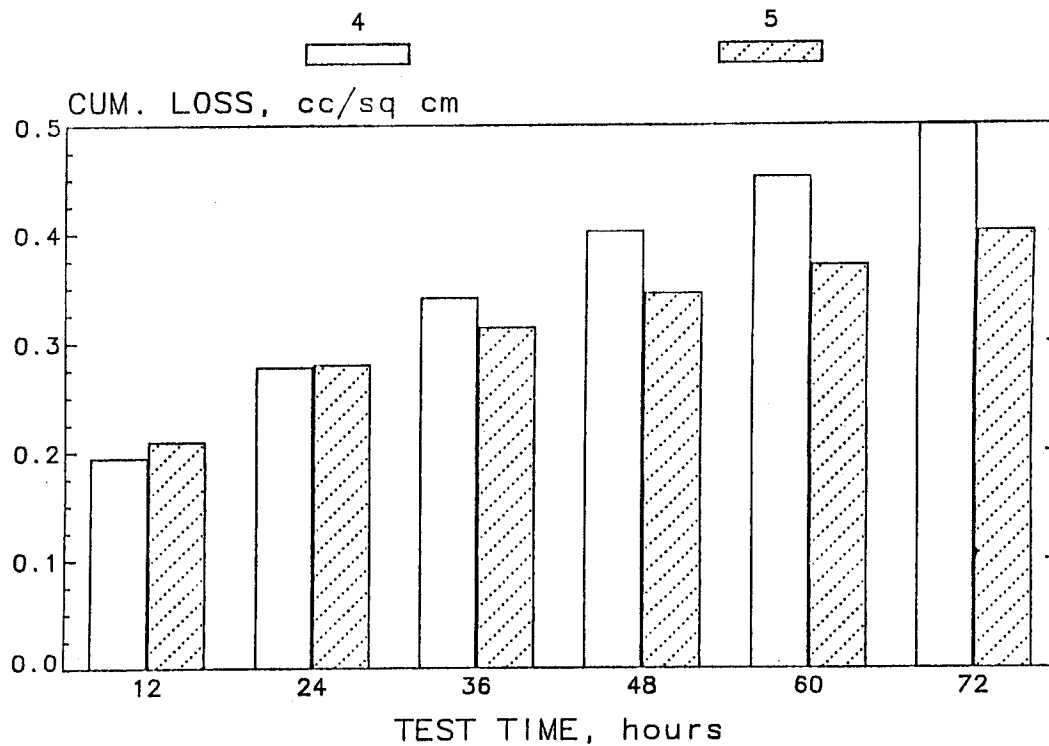


Figure 64. Abrasion-erosion data of conventional tremie concrete mixture no. 100

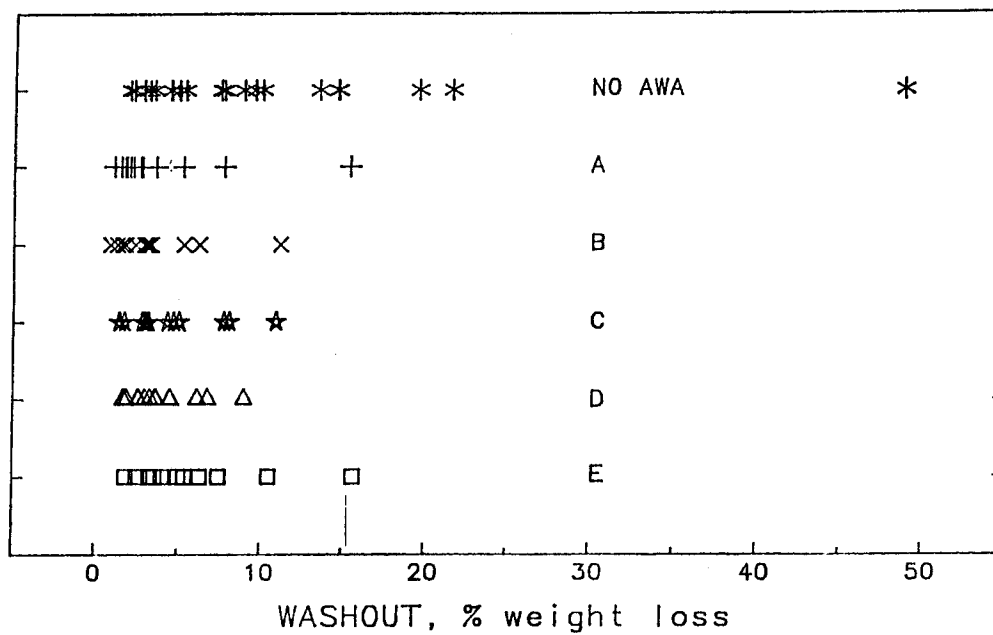


Figure 65. Washout data of concrete mixtures having different AWA's

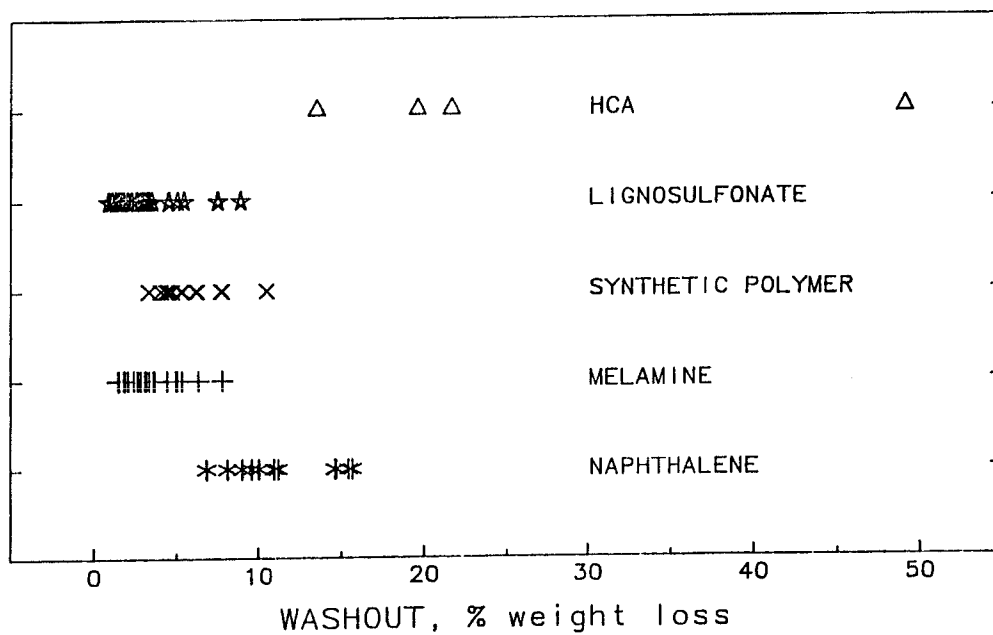


Figure 66. Washout data of concrete mixtures having different HRWR's

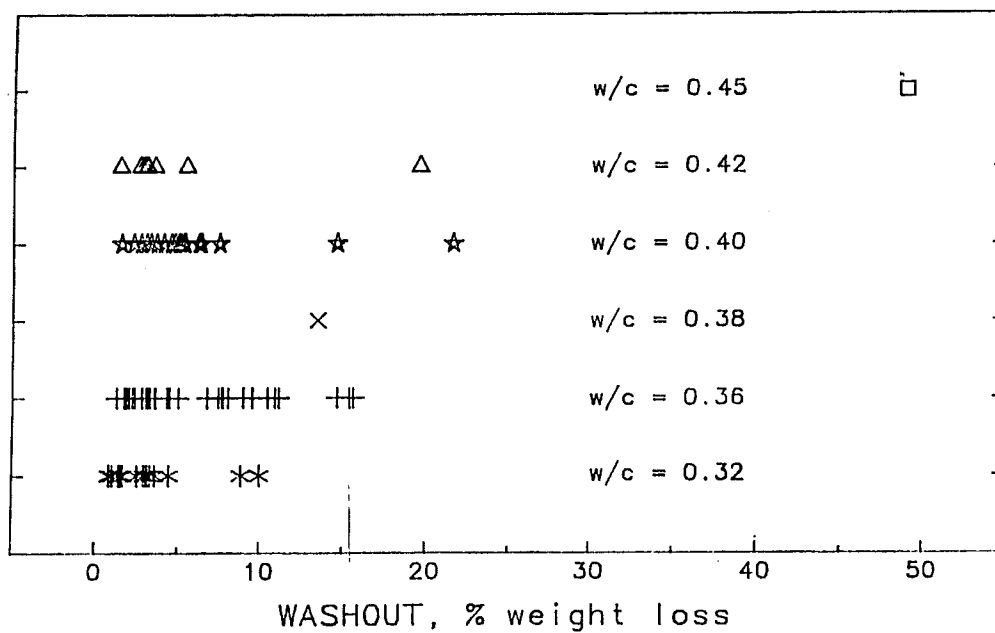


Figure 67. Washout data of concrete mixtures having different W/C's

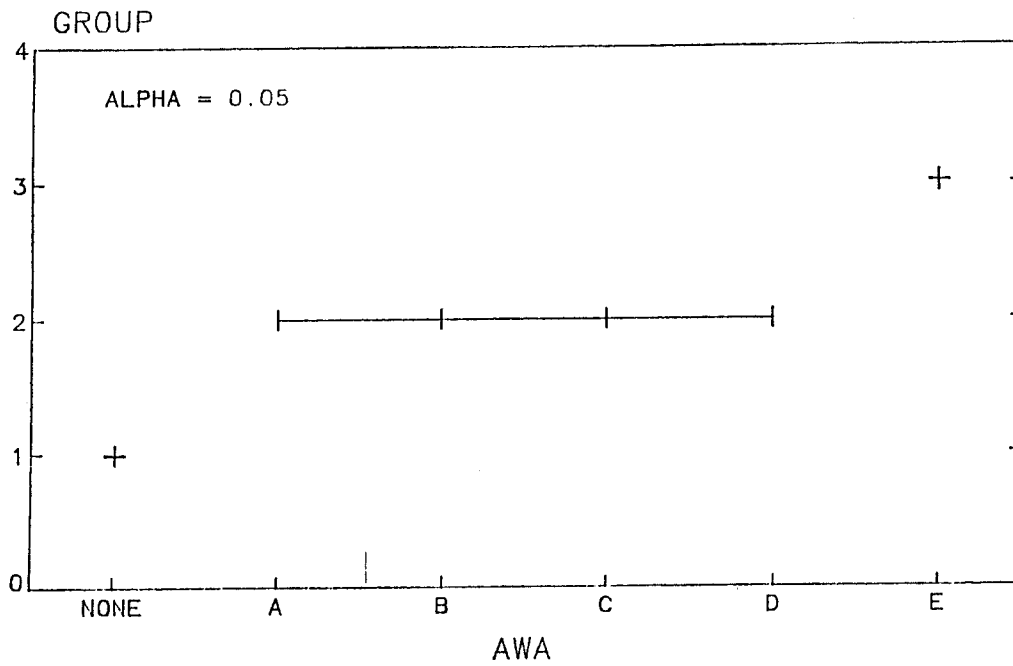


Figure 68. Duncan's multiple range grouping for washout data based upon AWA

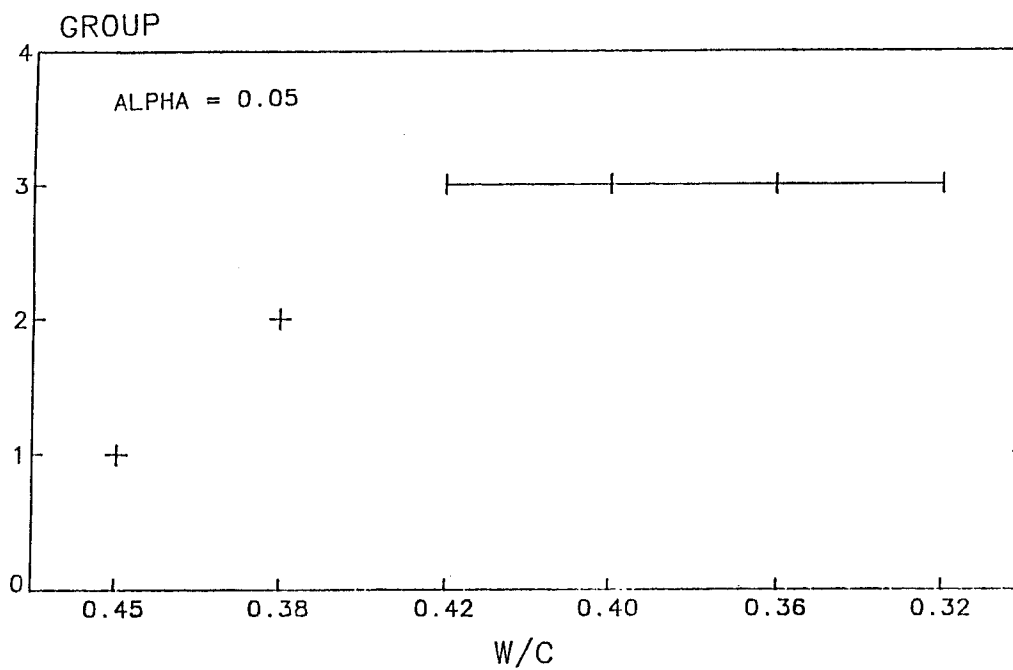


Figure 69. Duncan's multiple range grouping for washout data based upon W/C

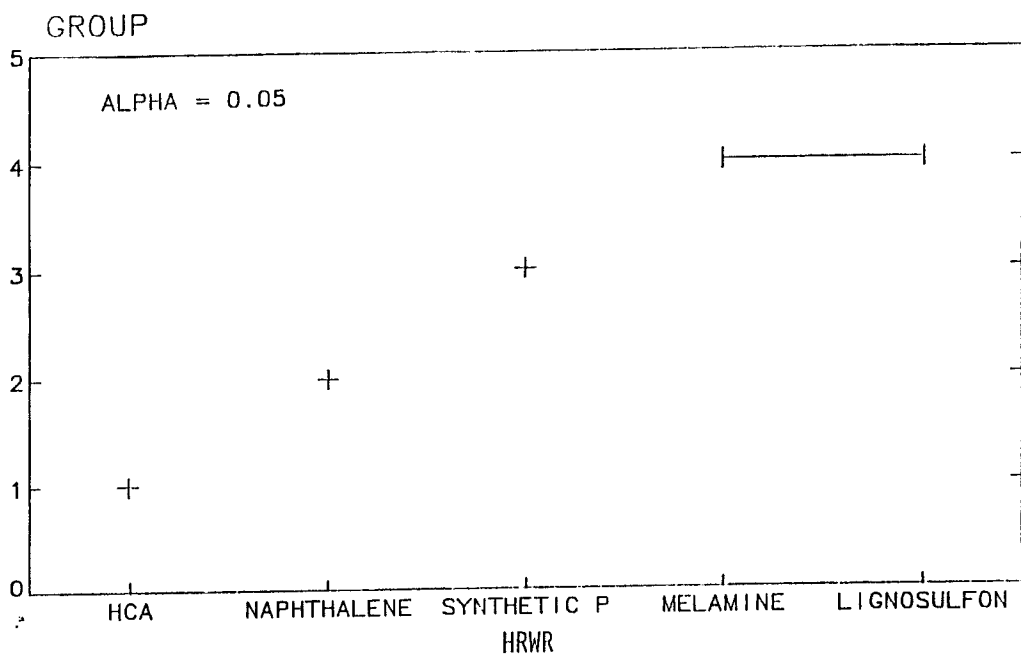


Figure 70. Duncan's multiple range grouping for washout data based upon HRWR

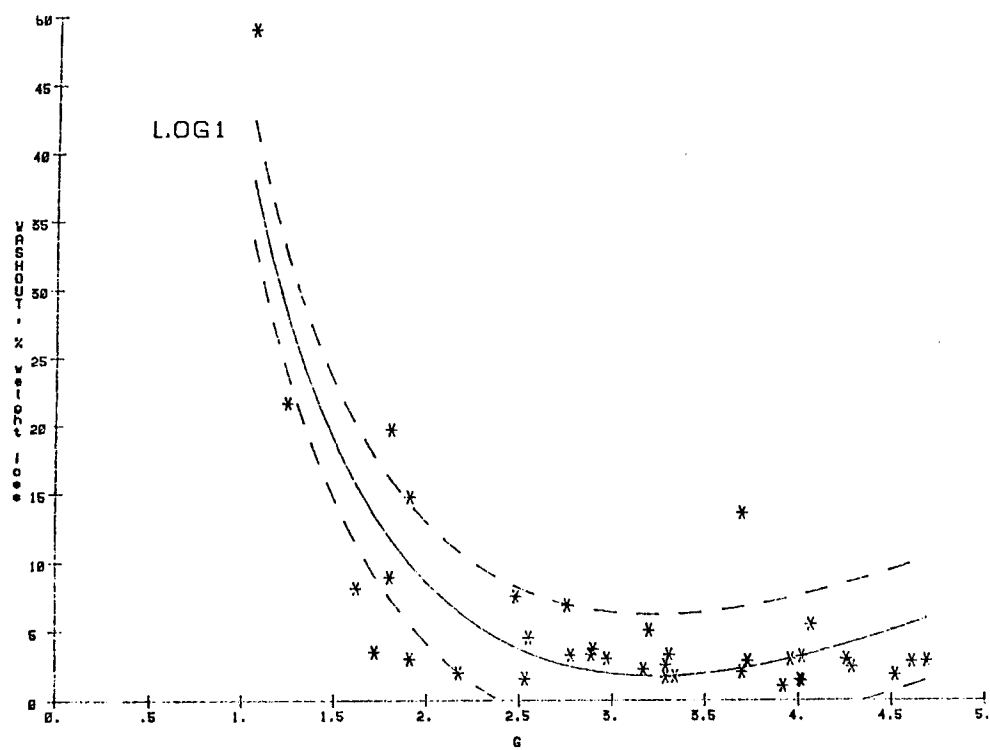


Figure 71. Common log 1 curve of washout data versus G

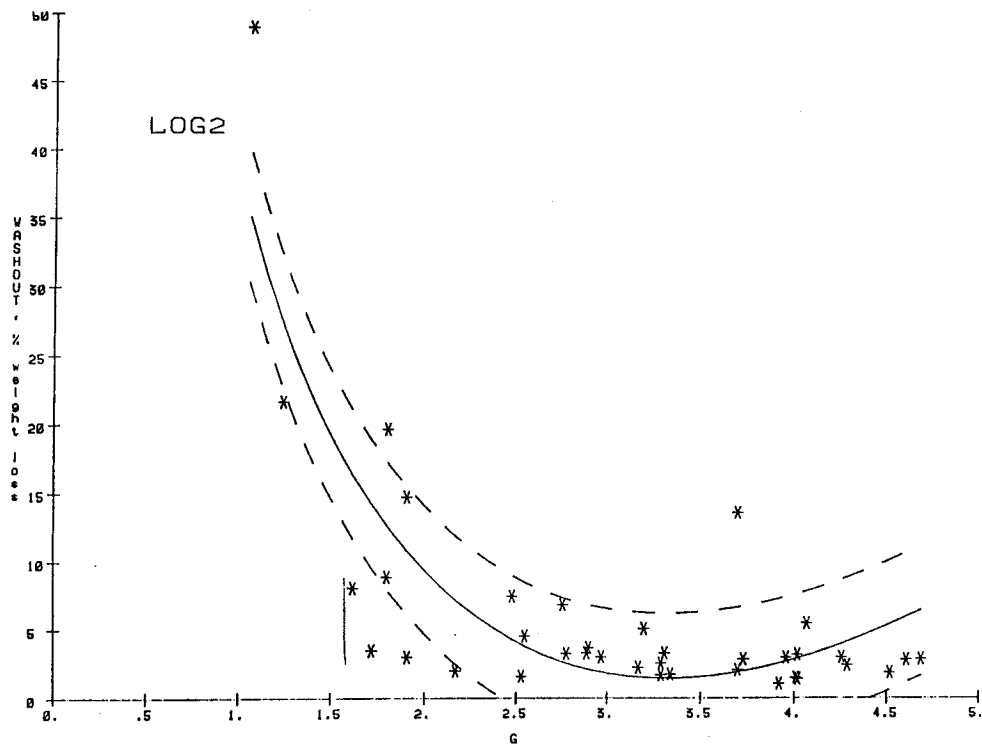


Figure 72. Common log 2 curve of washout data versus G

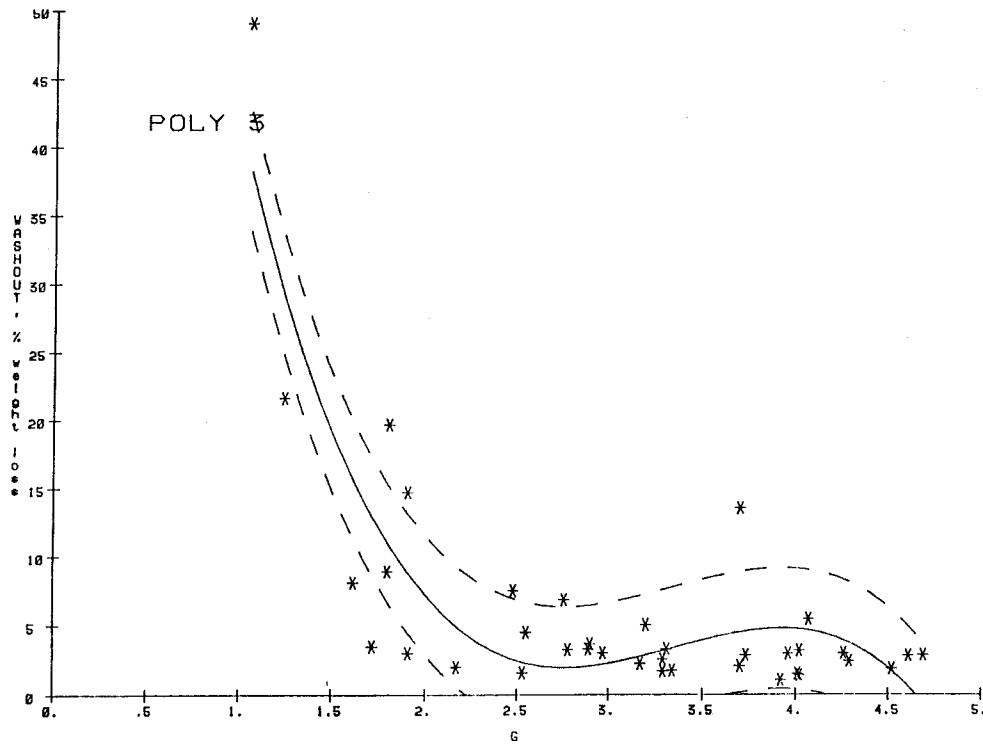


Figure 73. Third-degree polynomial curve of washout data versus G

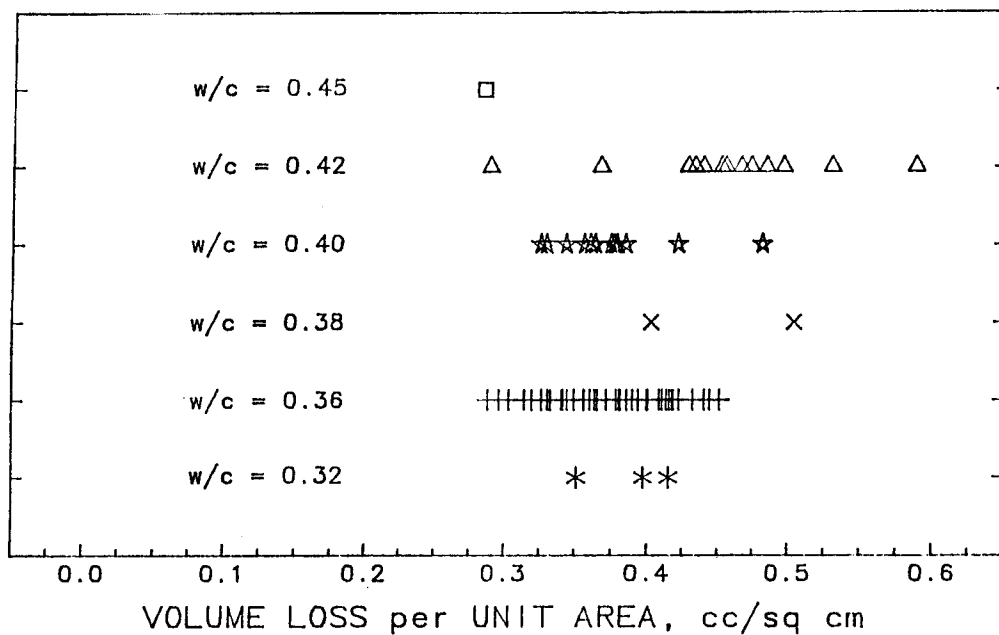


Figure 74. Abrasion-erosion characteristics of concrete mixtures having different W/C's

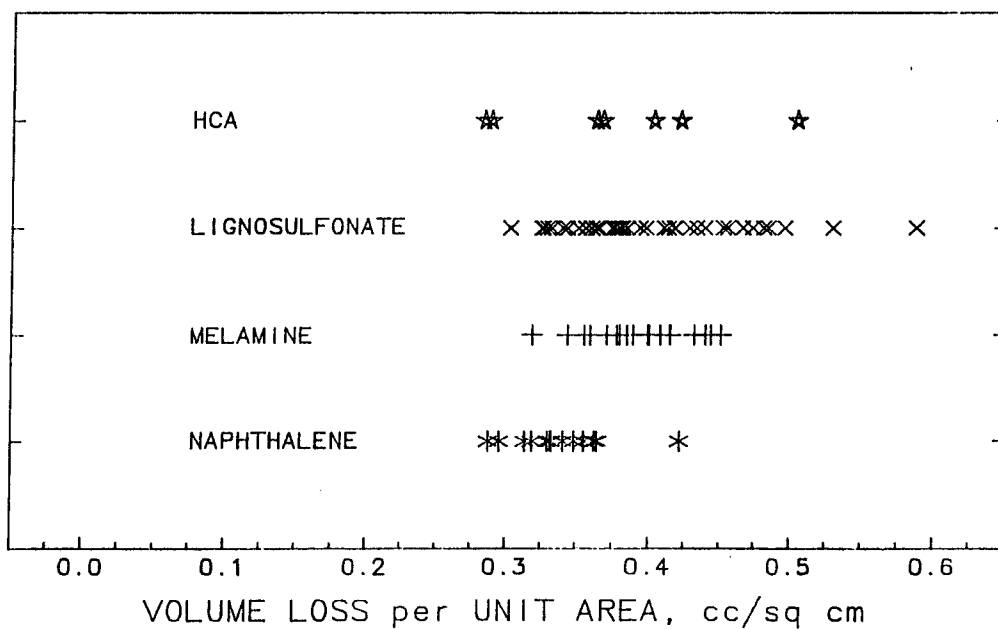


Figure 75. Abrasion-erosion characteristics of concrete mixtures having different HRWR's

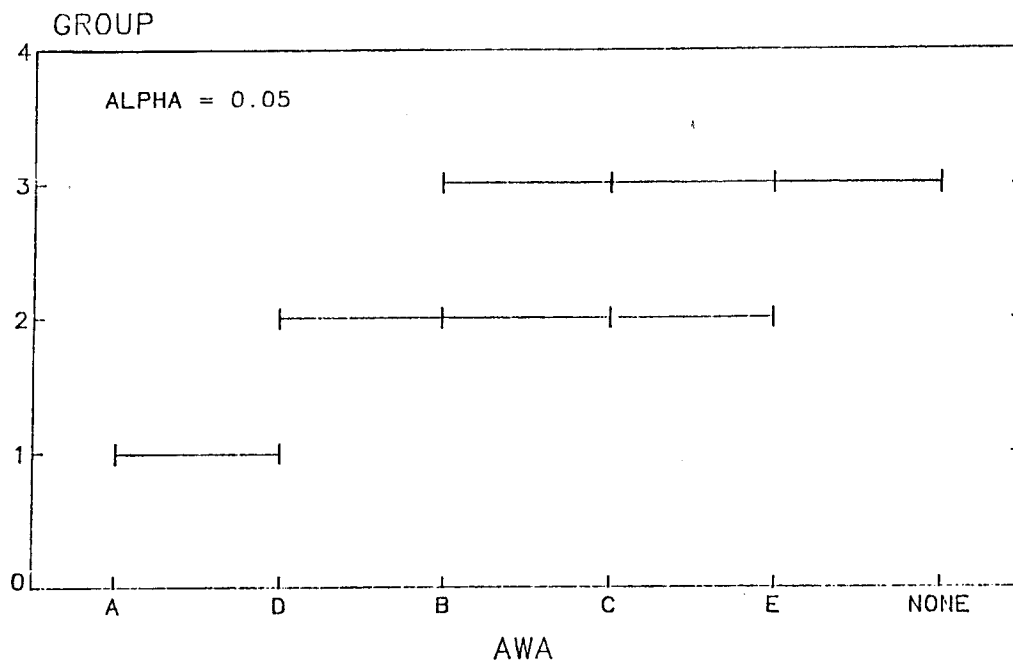


Figure 76. Duncan's multiple range grouping for abrasion-erosion characteristics based upon AWA

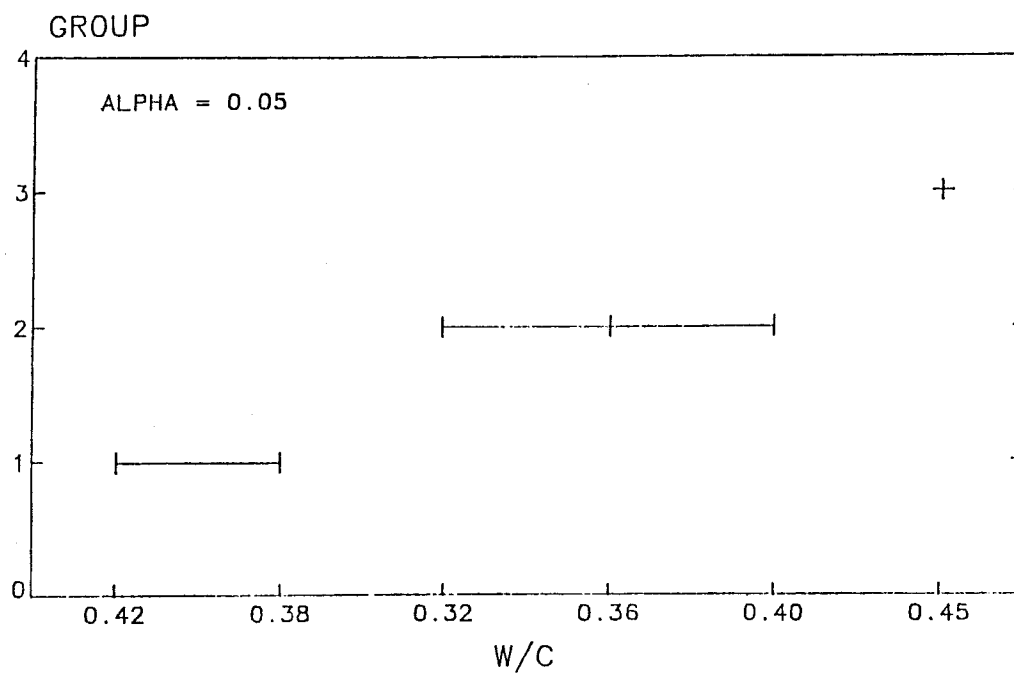


Figure 77. Duncan's multiple range grouping for abrasion-erosion characteristics based upon W/C

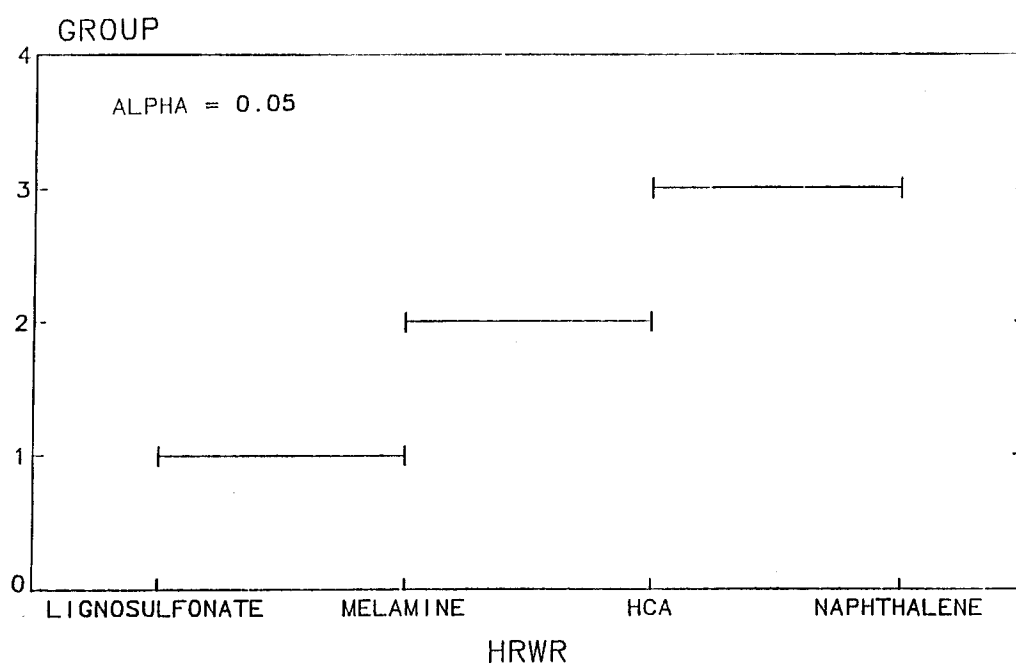


Figure 78. Duncan's multiple range grouping for abrasion-erosion characteristics based upon HRWR

Table 1
Phase I Test Matrix

AWA	HRWR		
	Naphthalene	Melamine	Synthetic Polymer
None	x y z	x y z	x y z
A	y	x y z	x y
B	y	x y z	x y
C	y	x y z	x y
D	y	x y z	x y
E	y	x y z	x y

x---W/C = 0.40, 590 lb of cement, 15 percent silica fume addition.

y---W/C = 0.36, 590 lb of cement, 15 percent silica fume addition.

z---W/C = 0.32, 700 lb of cement, 15 percent silica fume addition, 15 percent class F fly ash addition.

Table 2
Composition of AWA's

AWA	Organic Substances		Inorganic Substances		Manufacturer's Recommended Dosage	Other Information
	% by Mass	Type	% by Mass	Type		
A	100	Cellulose and water reducer			0.5 - 1.0% by wt of cement	Light brown/yellow free-flowing powder. Maximum particle size = 125 μ m.
B	62	Cellulose and short fibers = 250 μ m long	38	Fine powder; particle size = 100 μ m	1.5% by wt of cement	White powder, not free-flowing. Aspect ratio of fiber = 5.5. Admixture = 50% fiber by volume.
C	49	Cellulose, water reducer, and short fibers = 360 μ m long	51	Fine powder; mainly calcite and feldspar; particle size = 30 μ m	17 - 59 lb/yd ³ of concrete	White/gray powder, not free-flowing Aspect ratio of fiber = 8.0; admixture = 20% organic powder, 35% filler, and 45% fibers by volume. Is corrosive.
D	10	Cellulose and short fibers	90	Fine powder - probably silica fume	42 lb/yd ³ of concrete	Dark gray, very fine powder. Loss on ignition = 6.8%
E	100	Polyethylene oxide			0.1 lb/yd ³ of concrete	White, free-flowing powder.

Table 3
Phase II Test Matrix

AWA	HRWR				Hydroxylated Carboxylic Acid (HCA)
	Naphthalene	Melamine	Lignosulfonate		
None	y	y	w x y z	r s t u v	
A		y	w x y z	r	
B		y	w x y z	r	
C	y	y	w x y z	r	
D	y	y	w x y z	r	
E		y	w x y z	r	

r---W/C = 0.354, 353 lb of cement, 353 lb of class F fly ash.
 s---W/C = 0.375, 353 lb of cement, 353 lb of class F fly ash.
 t---W/C = 0.40, 353 lb of cement, 353 lb of class F fly ash.
 u---W/C = 0.42, 705 lb of cement.
 v---W/C = 0.45, 705 lb of cement.
 w---W/C = 0.42, 549 lb of cement, 11 percent silica fume addition, 11 percent
 class F fly ash addition.
 x---W/C = 0.40, 590 lb of cement, 15 percent silica fume addition.
 y---W/C = 0.36, 590 lb of cement, 15 percent silica fume addition.
 z---W/C = 0.32, 700 lb of cement, 15 percent silica fume addition, 15 percent
 class F fly ash addition.

Table 4
Mixture Proportion, 1Control (1 cu yd)

<u>Materials</u>	<u>S.S.D. Weight lb</u>	<u>Solid Volume cu ft</u>
Portland cement	590.0	3.040
Silica fume	89.0	0.648
Fine aggregate	1,352.5	8.273
Coarse aggregate	1,608.9	10.111
HRWR	3.7	0.035
Water	271.6	4.353
Air		0.540
Total	3,915.7	27.000

W/C = 0.40 by mass based on total cementitious materials.
S/A = 45% by volume.

Slump = 8-3/4 in.
Air content = 2.4%.
Unit weight = 144.4 lb/cu ft.

Table 5
Mixture Proportion, 2Control (1 cu yd)

<u>Materials</u>	<u>S.S.D. Weight lb</u>	<u>Solid Volume cu ft</u>
Portland cement	700.0	3.607
Silica fume	105.0	0.765
Fly ash	105.0	0.701
Fine aggregate	1,090.6	6.671
Coarse aggregate	1,592.3	10.007
HRWR	4.1	0.042
Water	291.2	4.667
Air		0.540
Total	3,888.2	27.000

W/C = 0.32 by mass based on total cementitious materials.
S/A = 40% by volume.

Slump = 6-3/4 in.
Air content = 1.2%.
Unit weight = 145.2 lb/cu ft.

Table 6
Mixture Proportion, 3Control (1 cu yd)

<u>Materials</u>	<u>S.S.D. Weight lb</u>	<u>Solid Volume cu ft</u>
Portland cement	590.0	3.040
Silica fume	89.0	0.648
Fine aggregate	1,402.5	8.575
Coarse aggregate	1,667.7	10.481
HRWR	6.8	0.069
Water	244.4	3.917
Air		0.270
Total	3,999.9	27.000

W/C = 0.36 by mass based on total cementitious content.

S/A = 45% by volume.

Slump = 8-1/4 in.

Air content = 2.1%.

Unit weight = 146.4 lb/cu ft.

Table 7
Aggregate Data

Type of material: Natural chert

<u>Sieve Size</u>	<u>Cumulative Percent Passing</u>	
	<u>Coarse Aggregate</u>	<u>Fine Aggregate</u>
37.5 mm (1-1/2 in.)	100	
25.0 mm (1 in.)	91	
19.0 mm (3/4 in.)	62	
12.5 mm (1/2 in.)	33	
9.5 mm (3/8 in.)	16	100
4.75 mm (# 4)	2	98
2.36 mm (# 8)	1	92
1.18 mm (# 16)		86
600 m (# 30)		75
300 m (# 50)		26
150 m (# 100)		2
Bulk specific gravity	2.56	2.62
Absorption, percent	1.30	0.39

Table 8
Results of Cement Tests

Specification: ASTM C 150, Type I	
Chemical Properties	Percent
SiO ₂	20.8
Al ₂ O ₃	4.6
Fe ₂ O ₃	2.4
MgO	3.8
SO ₃	2.5
Loss on ignition	1.4
Total alkalies as Na ₂ O	0.30
Na ₂ O	0.04
K ₂ O	0.39
Insoluble residue	0.14
CaO	63.5
C ₃ S	59
C ₃ A	8
C ₂ S	16
C ₃ A + C ₃ S	67
C ₄ AF	7
C ₄ AF + 2C ₃ A	24
Physical Properties:	
Surface area	364 m ² /kg
Air content	11 %
Compressive strength at 3 days	2,540 psi
Compressive strength at 7 days	3,520 psi
Autoclave expansion	0.80%
Time of initial setting	2 hr 30 min
Time of final setting	4 hr 30 min
Specific gravity	3.11

Table 9
Results of Fly Ash Tests

Specification: ASTM C 618, Class F

Chemical Properties

$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$	84.9%
MgO	0.9%
SO_3	1.1%
Loss on ignition	1.6%
Moisture content	0.3%

Physical Properties:

Pozzolanic strength	113% of control
Autoclave expansion	0.04%
Fineness	19% retained on #325
Lime-pozzolan strength	1,190 psi
Water requirement	92% of control
Specific gravity	2.40

Table 10
Results of Silica Fume Tests

<u>Kind of pozzolan: Silica fume</u>	
Chemical Properties	
$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$	94.5%
MgO	0.3%
SO_3	0.4%
SiO_2	93.6%
Al_2O_3	0.8%
Fe_2O_3	0.1%
CaO	0.2%
Total alkalis as Na_2O	0.57%
Na_2O	0.31%
K_2O	0.40%
Loss on ignition	1.5%
Moisture content	0.5%
Physical Properties:	
Pozzolanic strength	191% of control
Autoclave expansion	-0.13%
Fineness	3% retained on #325
Lime-pozzolan strength	2,160 psi
Water requirement	112% of control
Specific gravity	2.20

Table 11

Mixture Proportions of Concrete Mixtures Containing Powdered HRWR, Phase I

Mix No.	W/C	HRWR	Dosage lb/cu yd	AWA	Dosage lb/cu yd	Cement lb/cu yd	Silica Fume lb/cu yd	Fly Ash lb/cu yd	Fine Aggregate lb/cu yd	Coarse Aggregate lb/cu yd	Water lb/cu yd	Deair lb/cu yd
1Control	0.40	NAPHTHALENE	3.74	NONE	NONE	590	89	NONE	1,353	1,609	272	NONE
2Control	0.32	NAPHTHALENE	4.10	NONE	NONE	700	105	105	1,091	1,592	291	NONE
3Control	0.36	NAPHTHALENE	6.79	NONE	NONE	590	89	NONE	1,402	1,668	244	NONE
38	0.36	NAPHTHALENE	6.79	B	1.02	590	89	NONE	1,402	1,668	244	NONE
39	0.36	NAPHTHALENE	20.37	A	0.68	590	89	NONE	1,402	1,668	244	NONE
40	0.36	NAPHTHALENE	6.79	C	2.04	590	89	NONE	1,402	1,668	244	NONE
41	0.36	NAPHTHALENE	12.22	D	8.82	590	89	NONE	1,402	1,668	244	NONE
42	0.36	NAPHTHALENE	9.57	E	0.07	590	89	NONE	1,402	1,668	244	NONE
4Control	0.40	MELAMINE	3.74	NONE	NONE	590	89	NONE	1,353	1,609	272	NONE
5Control	0.32	MELAMINE	4.10	NONE	NONE	700	105	105	1,091	1,592	291	NONE
6Control	0.36	MELAMINE	6.11	NONE	NONE	590	89	NONE	1,402	1,668	244	NONE
43	0.36	MELAMINE	6.79	A	1.02	590	89	NONE	1,402	1,668	244	NONE
44	0.36	MELAMINE	6.79	B	3.40	590	89	NONE	1,402	1,668	244	NONE
45	0.36	MELAMINE	6.79	C	4.76	590	89	NONE	1,402	1,668	244	0.68
46	0.36	MELAMINE	6.79	D	6.80	590	89	NONE	1,402	1,668	244	1.02
47	0.36	MELAMINE	6.79	E	1.16	590	89	NONE	1,402	1,668	244	0.34
53	0.32	MELAMINE	5.46	A	1.82	700	105	105	1,091	1,592	291	0.68
54	0.32	MELAMINE	5.46	B	2.73	700	105	105	1,091	1,592	291	0.91
55	0.32	MELAMINE	5.46	C	10.01	700	105	105	1,091	1,592	291	0.91
56	0.32	MELAMINE	5.46	D	5.46	700	105	105	1,091	1,592	291	1.82
57	0.32	MELAMINE	5.46	E	1.82	700	105	105	1,091	1,592	291	0.91
58	0.40	MELAMINE	4.07	A	1.02	590	89	NONE	1,402	1,668	244	NONE
59	0.40	MELAMINE	4.07	B	1.36	590	89	NONE	1,402	1,668	244	0.34
60	0.40	MELAMINE	4.07	C	10.20	590	89	NONE	1,402	1,668	244	0.34
61	0.40	MELAMINE	4.75	D	3.40	590	89	NONE	1,402	1,668	244	1.02
62	0.40	MELAMINE	4.07	E	0.68	590	89	NONE	1,402	1,668	244	0.34

Table 12

Mixture Proportions of Concrete Mixtures Containing Liquid HRWR, Phase I

Mix No.	W/C	HRWR	Dosage lb/cu yd	AWA	Dosage lb/cu yd	Cement lb/cu yd	Silica Fume lb/cu yd	Fly Ash lb/cu yd	Fine Aggregate lb/cu yd	Coarse Aggregate lb/cu yd	Water lb/cu yd	Deair lb/cu yd
7Control	0.40	SYN POLY	109	NONE	NONE	590	89	NONE	1,353	1,609	268	NONE
8Control	0.32	SYN POLY	102	NONE	NONE	700	105	105	1,093	1,596	286	NONE
9Control	0.36	SYN POLY	170	NONE	NONE	590	89	NONE	1,405	1,671	238	NONE
48	0.36	SYN POLY	449	A	0.68	590	89	NONE	1,405	1,671	238	NONE
49	0.36	SYN POLY	170	B	2.04	590	89	NONE	1,405	1,671	238	0.68
50	0.36	SYN POLY	170	C	2.04	590	89	NONE	1,405	1,671	238	0.68
51	0.36	SYN POLY	170	D	2.04	590	89	NONE	1,405	1,671	238	NONE
52	0.36	SYN POLY	184	E	0.14	590	89	NONE	1,405	1,671	238	1.02
63	0.40	SYN POLY	122	A	0.68	590	89	NONE	1,353	1,609	268	1.02
64	0.40	SYN POLY	102	B	0.68	590	89	NONE	1,353	1,609	268	0.68
65	0.40	SYN POLY	109	C	2.04	590	89	NONE	1,353	1,609	268	0.68
66	0.40	SYN POLY	109	D	1.02	590	89	NONE	1,353	1,609	268	NONE
67	0.40	SYN POLY	122	E	0.07	590	89	NONE	1,353	1,609	268	NONE

Table 13
Mixture Proportion, 13Control (1 cu yd)

<u>Materials</u>	<u>S.S.D. Weight lb</u>	<u>Solid Volume cu ft</u>
Portland cement	549.2	2.800
Silica fume	61.0	0.444
Fly ash	61.0	0.407
Fine aggregate	1,585.5	9.698
Coarse aggregate	1,368.4	8.600
Lignosulfonate	40.3 oz	
Water	283.4	4.565
Air		<u>0.486</u>
Total	3,910.0	27.000

W/C = 0.424 by mass based on total cementitious materials.
S/A = 53% by volume.

Slump = 8-1/2 in.
Air content = 3.8%.
Unit weight = 142.4 lb/cu ft.

Table 14
Mixture Proportion, #99 (Gerwick, Holland, Komendant 1981*) (1 cu yd)

<u>Materials</u>	<u>S.S.D. Weight lb</u>	<u>Solid Volume cu ft</u>
Portland cement	705.0	3.587
Fine aggregate	1,354.8	8.287
Coarse aggregate	1,617.9	10.128
HCA	14.1 oz	
Water	295.0	4.728
Air		<u>0.270</u>
Total	3,972.7	27.000

W/C = 0.424 by mass.
S/A = 45% by volume.

Slump = 8-1/2 in.

* The first of six mixtures discussed in this reference.

Table 15

Mixture Proportion, #100 (Gerwick, Holland, Komendant, 1981*) (1 cu yd)

<u>Materials</u>	<u>S.S.D. Weight</u> <u>lb</u>	<u>Solid Volume</u> <u>cu ft</u>
Portland cement	353.0	1.796
Fly ash	353.0	2.357
Fine aggregate	1,348.5	8.249
Coarse aggregate	1,610.4	10.081
HCA	14.1 oz	
Water	265.0	4.247
Air		<u>0.270</u>
Total	3,629.9	27.000

W/C = 0.375 by mass based on total cementitious materials.

S/A = 45%.

Slump = 8-1/4 in.

* The sixth of six mixtures discussed in this reference.

Table 16

Mixture Proportions of Concrete Mixtures Containing Powdered HRWR, Phase II

Mix No.	W/C	HRWR	Dosage lb/cu yd	AWA	Dosage lb/cu yd	Cement lb/cu yd	Silica Fume lb/cu yd	Fly Ash lb/cu yd	Fine Aggregate lb/cu yd	Coarse Aggregate lb/cu yd	Water lb/cu yd	Deair lb/cu yd
6Control	0.36	MELAMINE	6.11	NONE	NONE	590	89	NONE	1,402	1,668	244	NONE
72	0.36	MELAMINE	6.79	D	6.79	590	89	NONE	1,402	1,668	244	0.34
73	0.36	MELAMINE	6.11	C	4.75	590	89	NONE	1,402	1,668	244	1.02
74	0.36	MELAMINE	6.79	B	3.40	590	89	NONE	1,402	1,668	244	0.68
75	0.36	MELAMINE	6.79	A	1.02	590	89	NONE	1,402	1,668	244	0.68
86	0.36	MELAMINE	6.79	E	1.15	590	89	NONE	1,402	1,668	244	0.68
73R	0.36	MELAMINE	7.81	C	4.75	590	89	NONE	1,402	1,668	244	1.02
74R	0.36	MELAMINE	8.15	B	3.40	590	89	NONE	1,402	1,668	244	0.68
75R1	0.36	MELAMINE	8.49	A	1.02	590	89	NONE	1,402	1,668	244	0.68
75R2	0.36	MELAMINE	8.49	A	1.02	590	89	NONE	1,402	1,668	244	0.68
3Control	0.36	NAPHTHALENE	6.11	NONE	NONE	590	89	NONE	1,402	1,668	244	NONE
76	0.36	NAPHTHALENE	6.79	C	2.04	590	89	NONE	1,402	1,668	244	1.36
96	0.36	NAPHTHALENE	12.22	D	17.65	590	89	NONE	1,402	1,668	244	1.36

Table 17

Mixture Proportions of Concrete Mixtures Containing Liquid HRWR, Phase II

Mix No.	W/C	HRWR	Dosage lb/cu yd	AWA	Dosage lb/cu yd	Cement lb/cu yd	Silica Fume lb/cu yd	Fly Ash lb/cu yd	Fine Aggregate lb/cu yd	Coarse Aggregate lb/cu yd	Water lb/cu yd	Deair lb/cu yd
12Control	0.36	LIGNOSUL	143	NONE	NONE	590	89	NONE	1,405	1,671	238	NONE
78	0.36	LIGNOSUL	170	D	6.79	590	89	NONE	1,405	1,671	238	0.68
79	0.36	LIGNOSUL	258	C	13.58	590	89	NONE	1,405	1,671	238	0.68
80	0.36	LIGNOSUL	170	B	3.40	590	89	NONE	1,405	1,671	238	0.68
87	0.36	LIGNOSUL	170	A	0.68	590	89	NONE	1,405	1,671	238	0.68
89	0.36	LIGNOSUL	170	E	0.68	590	89	NONE	1,405	1,671	238	0.68
79R	0.36	LIGNOSUL	197	C	1.02	590	89	NONE	1,405	1,671	238	0.68
80R	0.36	LIGNOSUL	197	B	3.40	590	89	NONE	1,405	1,671	238	0.68
87R	0.36	LIGNOSUL	204	A	0.68	590	89	NONE	1,405	1,671	238	0.68
12CONR	0.36	LIGNOSUL	204	NONE	NONE	590	89	NONE	1,405	1,671	238	0.68
13Control	0.42	LIGNOSUL	40	NONE	NONE	549	61	61	1,586	1,368	285	NONE
81	0.42	LIGNOSUL	40	C	10.06	549	61	61	1,586	1,368	285	NONE
82	0.42	LIGNOSUL	60	D	10.06	549	61	61	1,586	1,368	285	0.68
83	0.42	LIGNOSUL	54	B	3.36	549	61	61	1,586	1,368	285	0.68
84	0.42	LIGNOSUL	67	A	1.34	549	61	61	1,586	1,368	285	0.68
85	0.42	LIGNOSUL	54	E	1.34	549	61	61	1,586	1,368	285	0.68
82R	0.42	LIGNOSUL	94	D	10.06	549	61	61	1,586	1,368	285	0.68
11Control	0.32	LIGNOSUL	91	NONE	NONE	700	105	105	1,093	1,596	288	NONE
69	0.32	LIGNOSUL	91	C	22.75	700	105	105	1,093	1,596	288	NONE
70	0.32	LIGNOSUL	109	E	2.73	700	105	105	1,093	1,596	288	NONE
71	0.32	LIGNOSUL	118	D	9.10	700	105	105	1,093	1,596	288	NONE
88	0.32	LIGNOSUL	109	B	2.73	700	105	105	1,093	1,596	288	0.91
90	0.32	LIGNOSUL	109	A	1.82	700	105	105	1,093	1,596	288	0.91
88R	0.32	LIGNOSUL	109	B	2.73	700	105	105	1,093	1,596	288	0.91
14Control	0.40	LIGNOSUL	95	NONE	NONE	590	89	NONE	1,353	1,609	269	NONE
91	0.40	LIGNOSUL	102	A	2.04	590	89	NONE	1,353	1,609	269	0.68
92	0.40	LIGNOSUL	102	B	4.08	590	89	NONE	1,353	1,609	269	0.68
93	0.40	LIGNOSUL	102	C	17.00	590	89	NONE	1,353	1,609	269	0.68
94	0.40	LIGNOSUL	102	D	10.20	590	89	NONE	1,353	1,609	269	0.68
95	0.40	LIGNOSUL	102	E	1.36	590	89	NONE	1,353	1,609	269	0.68
97	0.45	HCA	14	NONE	NONE	705	NONE	NONE	1,329	1,580	317	NONE
98	0.40	HCA	14	NONE	NONE	353	NONE	353	1,287	1,530	317	NONE
99	0.42	HCA	14	NONE	NONE	705	NONE	NONE	1,355	1,612	295	NONE
100	0.38	HCA	14	NONE	NONE	353	NONE	353	1,349	1,604	265	NONE

Table 18

Data for Concrete Mixtures with Powdered HRWR, Phase I

Mix No.	W/C	HRWR	Dosage % of Cement	AWA	Dosage, % of Cement	Slump, in.	Air Content, %	Loss @ 1 Drop, % weight	Loss @ 2 Drops, % weight	Loss @ 3 Drops, % weight	28-Day Strength, psi	D-Air 1 % of cement
1Control	0.40	NAPHTHALENE	0.55	NONE	NONE	---	2.40	5.87	9.61	14.63	5,830	NONE
2Control	0.32	NAPHTHALENE	0.45	NONE	NONE	6.75	1.20	6.13	8.30	10.04	6,660	NONE
3Control	0.36	NAPHTHALENE	1.00	NONE	NONE	8.25	2.10	4.81	7.76	9.57	6,790	NONE
38	0.36	NAPHTHALENE	1.00	B	0.15	5.50	14.70	4.13	7.85	11.20	3,180	NONE
39	0.36	NAPHTHALENE	3.00	A	0.10	7.75	---	8.40	11.91	15.45	2,940	NONE
40	0.36	NAPHTHALENE	1.00	C	0.30	8.00	14.20	6.01	9.03	10.96	4,820	NONE
41	0.36	NAPHTHALENE	1.80	D	1.30	8.00	2.00	3.50	7.52	9.01	7,200	NONE
42	0.36	NAPHTHALENE	1.41	E	0.01	9.25	2.50	4.30	9.70	15.68	7,270	NONE
4Control	0.40	MELAMINE	0.55	NONE	NONE	8.00	1.60	1.52	3.54	4.96	7,050	NONE
5Control	0.32	MELAMINE	0.45	NONE	NONE	7.25	1.10	0.76	1.78	3.15	6,270	NONE
6Control	0.36	MELAMINE	0.90	NONE	NONE	7.25	2.10	1.70	3.06	4.42	8,150	NONE
43	0.36	MELAMINE	1.00	A	0.15	8.00	14.20	1.49	2.69	3.62	8,090	NONE
44	0.36	MELAMINE	1.00	B	0.50	7.50	2.60	1.00	1.93	3.06	8,430	0.10
45	0.36	MELAMINE	1.00	C	0.70	8.25	2.40	1.93	4.44	7.78	9,080	0.15
46	0.36	MELAMINE	1.00	D	1.00	7.50	4.20	0.39	1.30	1.88	8,750	0.05
47	0.36	MELAMINE	1.00	E	0.17	7.00	1.80	1.64	2.52	3.59	8,540	0.10
53	0.32	MELAMINE	0.55	A	0.20	8.50	2.00	0.12	0.95	1.48	8,800	0.10
54	0.32	MELAMINE	0.55	B	0.30	7.25	1.80	0.94	2.15	3.11	8,210	0.10
55	0.32	MELAMINE	0.55	C	1.10	8.50	1.50	0.39	1.02	1.45	9,260	0.20
56	0.32	MELAMINE	0.55	D	0.60	7.00	1.60	0.70	1.74	2.62	7,730	0.10
57	0.32	MELAMINE	0.55	E	0.20	7.50	1.40	0.87	2.30	3.33	7,780	NONE
58	0.40	MELAMINE	0.60	A	0.15	7.00	3.00	0.97	1.90	2.68	7,470	0.05
59	0.40	MELAMINE	0.60	B	0.20	7.25	2.50	1.69	3.82	5.31	7,540	0.05
60	0.40	MELAMINE	0.60	C	1.50	8.75	1.60	2.57	4.00	5.04	8,480	0.15
61	0.40	MELAMINE	0.70	D	0.50	7.25	2.50	1.09	2.33	3.61	7,780	0.05
62	0.40	MELAMINE	0.60	E	0.10	7.50	1.80	2.84	4.61	6.33	7,530	0.05

Table 19

Data for Concrete Mixtures with Liquid HRWR, Phase I

Mix No.	W/C	HRWR	Dosage % of Cement	AWA	Dosage, % of Cement	Slump, in.	Air Content, %	Loss @ 1 Drop, % weight	Loss @ 2 Drops, % weight	Loss @ 3 Drops, % weight	28-Day Strength, psi	D-Air 1 % of cement
7Control	0.40	SYN POLY	16	NONE	NONE	8.00	0.80	2.39	4.07	5.34	6,390	NONE
8Control	0.32	SYN POLY	15	NONE	NONE	8.50	1.20	---	3.12	4.48	8,980	NONE
9Control	0.36	SYN POLY	25	NONE	NONE	9.00	1.80	4.24	6.32	7.70	6,610	NONE
48	0.36	SYN POLY	66	A	0.10	7.50	15.20	3.41	5.73	7.76	4,250	NONE
49	0.36	SYN POLY	25	B	0.30	5.50	2.80	1.10	2.49	3.31	9,200	0.10
50	0.36	SYN POLY	25	C	0.30	7.75	2.40	1.64	3.27	4.34	9,590	0.10
51	0.36	SYN POLY	25	D	0.30	7.75	4.00	1.42	3.25	4.52	8,310	NONE
52	0.36	SYN POLY	27	E	0.02	8.25	3.50	4.10	7.32	10.52	8,500	0.15
63	0.40	SYN POLY	18	A	0.10	7.25	4.80	1.80	3.75	5.26	6,400	0.15
64	0.40	SYN POLY	15	B	0.10	8.00	5.80	2.80	4.80	6.25	6,080	0.10
65	0.40	SYN POLY	16	C	0.30	7.50	3.00	1.69	3.43	4.72	7,360	0.10
66	0.40	SYN POLY	16	D	0.15	8.00	1.40	2.88	4.80	6.16	7,110	NONE
67	0.40	SYN POLY	18	E	0.01	7.50	1.00	2.07	4.04	5.70	6,880	NONE

Table 20

Data for Concrete Mixtures with Powdered HRWR, Phase II

Mix No.	W/C	HRWR	Dosage % of Cement	AWA	Dosage, % of Cement	Slump, in.	Air Content, %	D-Air 1 % of Cement	Loss @ 3 Drops, % weight	28-Day Strength, psi	Correlation Coefficient	G, Nm	H
6Control	0.36	MELAMINE	0.90	NONE	NONE	8.00	---	NONE	2.83	6,940	0.996	3.73	1.30
72	0.36	MELAMINE	1.00	D	1.00	7.75	---	0.05	3.66	6,810	0.999	2.90	1.84
73	0.36	MELAMINE	0.90	C	0.70	8.50	---	0.15	3.17	7,450	0.969	5.26	3.74
74	0.36	MELAMINE	1.00	B	0.50	8.00	---	0.10	1.79	7,830	0.984	6.93	2.06
75	0.36	MELAMINE	1.00	A	0.15	8.25	---	0.10	2.04	7,630	0.981	5.92	2.60
86	0.36	MELAMINE	1.00	E	0.17	7.25	3.00	0.10	1.85	10,310*	0.996	4.52	1.38
73R	0.36	MELAMINE	1.15	C	0.70	8.25	1.70	0.15	2.83	---	0.980	4.69	3.01
74R	0.36	MELAMINE	1.20	B	0.50	8.50	2.30	0.10	2.39	---	0.992	4.29	2.62
75R1	0.36	MELAMINE	1.25	A	0.15	8.50	2.00	0.10	1.84	---	---	---	---
75R2	0.36	MELAMINE	1.25	A	0.15	7.75	2.30	0.10	2.05	---	0.990	3.70	2.91
3Control	0.36	NAPHTHALENE	0.90	NONE	NONE	8.25	---	---	14.71	7,850	0.993	1.91	1.55
76	0.36	NAPHTHALENE	1.00	C	0.30	9.25	3.80	0.20	8.09	8,170	0.999	1.62	1.68
96	0.36	NAPHTHALENE	1.80	D	2.60	8.25	4.40	0.20	6.81	7,840	0.996	2.76	3.89

* 107 days age.

Table 21

Data for Concrete Mixtures with Liquid HRWR, Phase II

Mix No.	W/C	HRWR	Dosage oz/cwt of Cement	AWA	Dosage, % of Cement	Slump, in.	Air Content, %	D-Air 1 % of Cement	Loss @ 3 Drops, % Weight	28-Day Strength, psi	Correlation Coefficient	G, Nm	H
12Control	0.36	LIGNOSUL.	21.00	NONE	NONE	8.00	8.20	NONE	7.49	6,490	0.978	2.56	0.98
78	0.36	LIGNOSUL.	25.00	D	1.00	7.00	1.20	0.10	3.29	9,890††	0.934	2.89	3.48
79	0.36	LIGNOSUL.	38.00	C	2.00	8.00	2.20	0.10	1.74	6,770	0.851	5.64	2.59
80	0.36	LIGNOSUL.	25.00	B	0.50	7.50	2.70	0.10	1.28	9,000	0.985	4.54	2.11
87	0.36	LIGNOSUL.	25.00	A	0.10	7.25	2.80	0.10	2.25	10,660**	0.987	4.95	2.62
89	0.36	LIGNOSUL.	25.00	E	0.10	8.00	1.80	0.10	5.03	10,580*	0.991	5.20	1.43
79R	0.36	LIGNOSUL.	29.00	C	1.50	8.75	1.80	0.10	3.15	---	0.990	4.02	3.74
80R	0.36	LIGNOSUL.	29.00	B	0.50	8.75	2.80	0.10	3.28	---	0.995	3.31	2.18
87R	0.36	LIGNOSUL.	30.00	A	0.10	8.50	2.20	0.10	1.74	---	0.992	3.34	1.93
12CONR	0.36	LIGNOSUL.	30.00	NONE	NONE	8.50	2.70	0.10	2.00	---	0.990	2.17	1.06
13Control	0.42	LIGNOSUL.	6.00	NONE	NONE	8.50	3.80	NONE	3.48	8,400†	0.990	1.72	1.05
81	0.42	LIGNOSUL.	6.00	C	1.50	8.75	3.90	NONE	1.40	8,670†	0.998	4.02	1.58
82	0.42	LIGNOSUL.	9.00	D	1.50	7.25	3.60	0.10	2.59	8,020†	0.983	3.48	1.98
83	0.42	LIGNOSUL.	8.00	B	0.50	8.00	3.90	0.10	2.94	8,430†	0.997	3.96	1.56
84	0.42	LIGNOSUL.	10.00	A	0.20	6.50	3.70	0.10	2.78	8,310†	0.993	4.61	1.94
85	0.42	LIGNOSUL.	8.00	E	0.20	6.00	3.30	0.10	5.41	8,830†	0.990	4.07	0.67
82R	0.42	LIGNOSUL.	14.00	D	1.50	8.75	2.80	0.10	3.00	---	0.998	2.97	1.39
11Control	0.32	LIGNOSUL.	10.00	NONE	NONE	8.00	0.90	NONE	8.89	6,560	0.997	1.80	0.60
69	0.32	LIGNOSUL.	10.00	C	2.50	9.00	1.70	NONE	2.95	8,590	0.991	4.26	3.38
70	0.32	LIGNOSUL.	12.00	E	0.30	7.50	---	NONE	2.55	7,170	0.993	3.29	1.78
71	0.32	LIGNOSUL.	13.00	D	1.00	7.00	4.50	NONE	1.69	7,370	0.998	3.29	1.59
88	0.32	LIGNOSUL.	12.00	B	0.30	8.00	1.80	0.10	0.85	7,940	0.968	3.08	1.20
90	0.32	LIGNOSUL.	12.00	A	0.20	7.00	1.90	0.10	1.05	10,370*	0.995	3.92	1.72
88R	0.32	LIGNOSUL.	12.00	B	0.30	8.75	1.70	0.10	1.59	---	0.994	2.53	2.28
14Control	0.40	LIGNOSUL.	14.00	NONE	NONE	7.00	2.90	NONE	2.24	9,510*	0.997	3.17	0.95
91	0.40	LIGNOSUL.	15.00	A	0.30	8.50	2.30	0.10	1.49	7,880	0.991	4.01	2.18
92	0.40	LIGNOSUL.	15.00	B	0.60	9.00	3.30	0.10	3.25	6,920	0.993	2.78	2.20
93	0.40	LIGNOSUL.	15.00	C	2.60	9.00	2.00	0.20	3.00	8,270	0.991	1.91	1.12
94	0.40	LIGNOSUL.	15.00	D	1.50	7.50	2.10	0.10	4.50	8,140	0.996	2.55	2.04
95	0.40	LIGNOSUL.	15.00	E	0.20	7.75	1.80	0.10	7.46	8,580	0.999	2.48	0.99
97	0.45	HCA	2.00	NONE	NONE	9.75	---	NONE	49.00	5,620	0.990	1.06	0.81
98	0.4	HCA	2.00	NONE	NONE	9.25	---	NONE	21.64	3,370	0.980	1.25	0.87
99	0.42	HCA	2.00	NONE	NONE	8.50	---	NONE	19.60	5,610	0.995	1.81	0.98
100	0.38	HCA	2.00	NONE	NONE	8.25	---	NONE	13.52	3,700	0.993	3.70	1.66

* 77 days age.

†112 days age.

** 107 days age.

††146 days age.

Table 22
Data for Washout Statistical Analysis

Washout	AWA	W/C	HRWR	Fly Ash	Silica Fume
9.57	NONE	0.36	NAPHTHALENE	NO	YES
15.45	A	0.36	NAPHTHALENE	NO	YES
11.20	B	0.36	NAPHTHALENE	NO	YES
10.96	C	0.36	NAPHTHALENE	NO	YES
9.01	D	0.36	NAPHTHALENE	NO	YES
15.68	E	0.36	NAPHTHALENE	NO	YES
14.71	NONE	0.36	NAPHTHALENE	NO	YES
8.09	C	0.36	NAPHTHALENE	NO	YES
6.81	D	0.36	NAPHTHALENE	NO	YES
14.63	NONE	0.40	NAPHTHALENE	NO	YES
10.04	NONE	0.32	NAPHTHALENE	YES	YES
4.42	NONE	0.36	MELAMINE	NO	YES
3.62	A	0.36	MELAMINE	NO	YES
3.08	B	0.36	MELAMINE	NO	YES
7.78	C	0.36	MELAMINE	NO	YES
1.88	D	0.36	MELAMINE	NO	YES
3.59	E	0.36	MELAMINE	NO	YES
2.83	NONE	0.36	MELAMINE	NO	YES
2.04	A	0.36	MELAMINE	NO	YES
1.79	B	0.36	MELAMINE	NO	YES
3.17	C	0.36	MELAMINE	NO	YES
3.86	D	0.36	MELAMINE	NO	YES
1.85	E	0.36	MELAMINE	NO	YES
1.84	A	0.36	MELAMINE	NO	YES
2.39	B	0.36	MELAMINE	NO	YES
2.83	C	0.36	MELAMINE	NO	YES
2.05	A	0.36	MELAMINE	NO	YES
4.96	NONE	0.40	MELAMINE	NO	YES
2.68	A	0.40	MELAMINE	NO	YES
6.31	B	0.40	MELAMINE	NO	YES
5.04	C	0.40	MELAMINE	NO	YES
3.61	D	0.40	MELAMINE	NO	YES
6.33	E	0.40	MELAMINE	NO	YES
3.15	NONE	0.32	MELAMINE	YES	YES
1.48	A	0.32	MELAMINE	YES	YES
3.11	B	0.32	MELAMINE	YES	YES
1.45	C	0.32	MELAMINE	YES	YES
2.62	D	0.32	MELAMINE	YES	YES
3.33	E	0.32	MELAMINE	YES	YES
7.70	NONE	0.36	SYN POLY	NO	YES
7.76	A	0.36	SYN POLY	NO	YES
3.31	B	0.36	SYN POLY	NO	YES
4.34	C	0.36	SYN POLY	NO	YES
4.52	D	0.36	SYN POLY	NO	YES
10.52	E	0.36	SYN POLY	NO	YES

(Continued)

Table 22 (Concluded)

Washout	AWA	W/C	HRWR	Fly Ash	Silica Fume
5.34	NONE	0.40	SYN POLY	NO	YES
5.26	A	0.40	SYN POLY	NO	YES
6.25	B	0.40	SYN POLY	NO	YES
4.72	C	0.40	SYN POLY	NO	YES
6.16	D	0.40	SYN POLY	NO	YES
4.04	E	0.40	SYN POLY	NO	YES
4.48	NONE	0.32	SYN POLY	YES	YES
7.49	NONE	0.36	LIGNOSUL	NO	YES
2.25	A	0.36	LIGNOSUL	NO	YES
1.28	B	0.36	LIGNOSUL	NO	YES
1.74	C	0.36	LIGNOSUL	NO	YES
3.29	D	0.36	LIGNOSUL	NO	YES
5.03	E	0.36	LIGNOSUL	NO	YES
2.00	NONE	0.36	LIGNOSUL	NO	YES
1.74	A	0.36	LIGNOSUL	NO	YES
3.28	B	0.36	LIGNOSUL	NO	YES
3.15	C	0.36	LIGNOSUL	NO	YES
3.48	NONE	0.42	LIGNOSUL	YES	YES
2.78	A	0.42	LIGNOSUL	YES	YES
2.94	B	0.42	LIGNOSUL	YES	YES
1.40	C	0.42	LIGNOSUL	YES	YES
2.59	D	0.42	LIGNOSUL	YES	YES
5.41	E	0.42	LIGNOSUL	YES	YES
3.00	D	0.42	LIGNOSUL	YES	YES
8.89	NONE	0.32	LIGNOSUL	YES	YES
1.05	A	0.32	LIGNOSUL	YES	YES
0.85	B	0.32	LIGNOSUL	YES	YES
2.95	C	0.32	LIGNOSUL	YES	YES
1.69	D	0.32	LIGNOSUL	YES	YES
2.55	E	0.32	LIGNOSUL	YES	YES
1.69	B	0.32	LIGNOSUL	YES	YES
2.24	NONE	0.40	LIGNOSUL	NO	YES
1.49	A	0.40	LIGNOSUL	NO	YES
3.25	B	0.40	LIGNOSUL	NO	YES
3.00	C	0.40	LIGNOSUL	NO	YES
4.50	D	0.40	LIGNOSUL	NO	YES
7.46	E	0.40	LIGNOSUL	NO	YES
49.00	NONE	0.45	HCA	NO	NO
19.60	NONE	0.42	HCA	NO	NO
21.64	NONE	0.40	HCA	YES	NO
13.52	NONE	0.38	HCA	YES	NO

Table 23
Results of Duncan's Multiple Range Test
for the Effects of AWA on Washout Data

<u>Grouping</u>	<u>Mean</u>	<u>Number of Samples</u>	<u>AWA</u>
A	10.4845	20	None
B	5.9809	11	E
C	4.3300	14	C
C	4.1031	13	D
C	3.6779	14	A
C	3.5436	14	B

Groupings with the same letter are not significantly different.

Table 24
Results of Duncan's Multiple Range Test
for the Effects of W/C on Washout Data

<u>Grouping</u>	<u>Mean</u>	<u>Number of Samples</u>	<u>W/C</u>
A	49.000	1	0.45
B	13.520	1	0.38
C	5.895	20	0.40
C	5.358	41	0.36
C	5.150	8	0.42
C	3.282	15	0.32

Groupings with the same letter are not significantly different.

Table 25
Results of Duncan's Multiple Range Test
for the Effects of HRWR on Washout Data

<u>Grouping</u>	<u>Means</u>	<u>Number of Samples</u>	<u>HRWR</u>
A	25.9400	4	HCA
B	11.4682	11	NAPHTHALENE
C	5.7231	13	SYNTHETIC POLYMER
D	3.2811	28	MELAMINE
D	3.1453	30	LIGNOSULFONATE

Groupings with the same letter are not significantly different.

Table 26
Results of Duncan's Multiple Range Test
for the Effects of Fly Ash on Washout Data

<u>Grouping</u>	<u>Means</u>	<u>Number of Samples</u>	<u>Fly Ash</u>
A	6.2024	62	NO
B	4.4162	24	YES

Groupings with the same letter are not significantly different.

Table 27
Results of Duncan's Multiple Range Test for
the Effects of Silica Fume on Washout Data

<u>Grouping</u>	<u>Means</u>	<u>Number of Samples</u>	<u>Silica Fume</u>
A	25.9400	4	NO
B	4.7168	82	YES

Groupings with the same letter are not significantly different.

Table 28
Washout, G, and H Data

<u>Washout</u>	<u>G</u>	<u>H</u>
2.83	3.73	1.30
3.66	2.90	1.84
1.85	4.52	1.38
2.83	4.69	3.01
2.39	4.29	2.62
2.05	3.70	2.91
14.71	1.91	1.55
8.09	1.62	1.68
6.81	2.76	3.89
3.29	2.89	3.48
5.03	3.20	1.43
3.15	4.02	3.74
3.28	3.31	2.18
1.74	3.34	1.93
2.00	2.17	1.08
3.48	1.72	1.06
1.40	4.02	1.58
2.94	3.96	1.56
2.78	4.61	1.94
5.41	4.07	0.67
3.00	2.97	1.39
8.89	1.80	0.60
2.95	4.26	3.38
2.55	3.29	1.78
1.69	3.29	1.59
0.85	3.08	1.20
1.05	3.92	1.72
1.59	2.53	2.28
2.24	3.17	0.95
1.49	4.01	2.18
3.25	2.78	2.20
3.00	1.91	1.12
4.50	2.55	2.04
7.46	2.48	0.99
49.00	1.06	1.06
21.64	1.25	1.25
19.65	1.81	1.81
13.52	3.70	3.70

Table 29

Y Estimate and Residual Values for Common Log 1 CurveCOMMON LOG(LOG1): $Y=A1+A2*LOG(X+X1)+A3*(LOG(X+X1))**2$

A1= 41.872555 A2= -157.56334

A3= 154.78063 X1= .00000000

<u>X Value</u>	<u>Y Value</u>	<u>Y Estimate</u>	<u>Residual</u>	<u>% Deviation</u>
1.060	49.000	37.984	11.0156	22.4808
1.250	21.640	28.057	-6.4167	29.6521
1.620	8.090	15.655	-7.5650	93.5106
1.720	3.480	13.348	-9.8682	283.5676
1.800	8.890	11.737	-2.8471	32.0259
1.810	19.650	11.549	8.1010	41.2263
1.910	3.000	9.817	-6.8165	227.2179
1.910	14.710	9.817	4.8935	33.2662
2.170	2.000	6.381	-4.3808	219.0400
2.480	7.460	3.804	3.6559	49.0070
2.530	1.590	3.508	-1.9183	120.6506
2.550	4.500	3.398	1.1019	24.4871
2.760	6.810	2.491	4.3191	63.4225
2.780	3.250	2.426	0.8236	25.3426
2.890	3.290	2.132	1.1585	35.2125
2.900	3.660	2.110	1.5505	42.3627
2.970	3.000	1.977	1.0233	34.1088
3.170	2.240	1.783	0.4567	20.3897
3.200	5.030	1.776	3.2542	64.6955
3.290	1.690	1.784	-0.0940	5.5598
3.290	2.550	1.784	0.7660	30.0407
3.310	3.280	1.792	1.4883	45.3744
3.340	1.740	1.807	-0.0672	3.8646
3.700	2.050	2.316	-0.2662	12.9863
3.700	13.520	2.316	11.2038	82.8682
3.730	2.830	2.382	0.4476	15.8161
3.920	1.050	2.873	-1.8234	173.6576
3.960	2.940	2.991	-0.0515	1.7506
4.010	1.490	3.146	-1.6557	111.1208
4.020	1.400	3.177	-1.7774	126.9576
4.020	3.150	3.177	-0.0274	0.8700
4.070	5.410	3.340	2.0699	38.2600
4.260	2.950	4.018	-1.0680	36.2042
4.290	2.390	4.133	-1.7431	72.9319
4.520	1.850	5.080	-3.2296	174.5724
4.610	2.780	5.478	-2.6983	97.0621
4.690	2.830	5.845	-3.0148	106.5306

SUM SQR RESIDUALS = 697.67441

NONLINEAR CORR = 0.8638931

STD ERROR EST = 4.34236

Table 30

Y Estimate and Residual Values for Common Log 2 CurveCOMMON LOG(LOG2): $Y=A1+A2*(X+X1)+A3*LOG(X+X1)$

A1= 16.000334 A2= 21.974353

A3= -167.90190 X1= .00000000

<u>X Value</u>	<u>Y Value</u>	<u>Y Estimate</u>	<u>Residual</u>	<u>% Deviation</u>
1.060	49.000	35.044	13.9558	28.4811
1.250	21.640	27.197	-5.5569	25.6788
1.620	8.090	16.421	-8.3308	102.9767
1.720	3.480	14.251	-10.7705	309.4985
1.800	8.890	12.693	-3.8034	42.7832
1.810	19.650	12.509	7.1408	36.3400
1.910	3.000	10.785	-7.7853	259.5103
1.910	14.710	10.785	3.9247	26.6804
2.170	2.000	7.192	-5.1924	259.6224
2.480	7.460	4.268	3.1925	42.7943
2.530	1.590	3.911	-2.3207	145.9588
2.550	4.500	3.776	0.7239	16.0875
2.760	6.810	2.620	4.1899	61.5261
2.780	3.250	2.533	0.7169	22.0594
2.890	3.290	2.121	1.1694	35.5444
2.900	3.660	2.088	1.5715	42.9385
2.970	3.000	1.887	1.1125	37.0848
3.170	2.240	1.530	0.7098	31.6863
3.200	5.030	1.503	3.5274	70.1267
3.290	1.690	1.458	0.2322	13.7407
3.290	2.550	1.458	1.0922	42.8321
3.310	3.280	1.455	1.8247	55.6300
3.340	1.740	1.457	0.2834	16.2845
3.700	2.050	1.903	0.1467	7.1565
3.700	13.520	1.903	11.6167	85.9224
3.730	2.830	1.974	0.8563	30.2591
3.920	1.050	2.526	-1.4759	140.5652
3.960	2.940	2.665	0.2754	9.3668
4.010	1.490	2.848	-1.3584	91.1679
4.020	1.400	2.887	-1.4865	106.1806
4.020	3.150	2.887	0.2635	8.3642
4.070	5.410	3.084	2.3261	42.9964
4.260	2.950	3.932	-0.9820	33.2885
4.290	2.390	4.080	-1.6895	70.6912
4.520	1.850	5.325	-3.4754	187.8605
4.610	2.780	5.865	-3.0855	110.9876
4.690	2.830	6.369	-3.5389	125.0478

SUM SQR RESIDUALS = 821.76433

NONLINEAR CORR = 0.8373708

STD ERROR EST = 4.71273

Table 31

Y Estimate and Residual Values for 3rd-Degree Polynomial CurvePOLYNOMIAL: 3 $Y=A1+A2*(X+X)+...+AN*(X+X1)**(N-1)$

X1= .00000

TERM(N) COEFFICIENT(A)

1	126.87723	3	36.516506
2	-118.28657	4	-3.6445024

<u>X Value</u>	<u>Y Value</u>	<u>Y Estimate</u>	<u>Residual</u>	<u>% Deviation</u>
1.060	49.000	38.183	10.8172	22.0760
1.250	21.640	28.958	-7.3179	33.8166
1.620	8.090	15.592	-7.5022	92.7343
1.720	3.480	12.910	-9.4299	270.9744
1.800	8.890	11.020	-2.1302	23.9613
1.810	19.650	10.799	8.8507	45.0416
1.910	3.000	8.771	-5.7713	192.3779
1.910	14.710	8.771	5.9387	40.3716
2.170	2.000	4.907	-2.9073	145.3647
2.480	7.460	2.528	4.9319	66.1112
2.530	1.590	2.331	-0.7406	46.5815
2.550	4.500	2.264	2.2358	49.6841
2.760	6.810	1.950	4.8597	71.3608
2.780	3.250	1.953	1.2972	39.9142
2.890	3.290	2.049	1.2409	37.7161
2.900	3.660	2.064	1.5957	43.5995
2.970	3.000	2.196	0.8044	26.8123
3.170	2.240	2.764	-0.5239	23.3872
3.200	5.030	2.866	2.1638	43.0179
3.290	1.690	3.187	-1.4973	88.5994
3.290	2.550	3.187	-0.6373	24.9933
3.310	3.280	3.260	0.0196	0.5961
3.340	1.740	3.371	-1.6306	93.7098
3.700	2.050	4.523	-2.4729	120.6311
3.700	13.520	4.523	8.9971	66.5463
3.730	2.830	4.587	-1.7569	62.0828
3.920	1.050	4.790	-3.7398	356.1746
3.960	2.940	4.779	-1.8392	62.5590
4.010	1.490	4.735	-3.2453	217.8039
4.020	1.400	4.722	-3.3222	237.2999
4.020	3.150	4.722	-1.5722	49.9110
4.070	5.410	4.634	0.7760	14.3446
4.260	2.950	3.911	-0.9614	32.5890
4.290	2.390	3.735	-1.3448	56.2667
4.520	1.850	1.716	0.1343	7.2602
4.610	2.780	0.569	2.2113	79.5415
4.690	2.830	-0.639	3.4691	122.5828

SUM SQR RESIDUALS = 706.74946

NONLINEAR CORR = 0.8619812

STD ERROR EST = 4.37051

Table 32
Data for Abrasion-Erosion Statistical Analysis

Abrasion- Erosion cc/cu cm	AWA	W/C	HRWR	Fly Ash	Silica Fume
0.319	NONE	0.36	MELAMINE	NO	YES
0.444	NONE	0.36	MELAMINE	NO	YES
0.389	NONE	0.36	MELAMINE	NO	YES
0.332	NONE	0.36	LIGNOSUL	NO	YES
0.418	NONE	0.36	LIGNOSUL	NO	YES
0.439	NONE	0.42	LIGNOSUL	YES	YES
0.466	NONE	0.42	LIGNOSUL	YES	YES
0.376	NONE	0.40	LIGNOSUL	NO	YES
0.383	NONE	0.40	LIGNOSUL	NO	YES
0.284	NONE	0.45	HCA	NO	NO
0.289	NONE	0.42	HCA	NO	NO
0.367	NONE	0.42	HCA	NO	NO
0.421	NONE	0.40	HCA	YES	NO
0.383	NONE	0.40	HCA	YES	NO
0.504	NONE	0.38	HCA	YES	NO
0.402	NONE	0.38	HCA	YES	NO
0.415	A	0.36	MELAMINE	NO	YES
0.408	A	0.36	MELAMINE	NO	YES
0.356	A	0.36	MELAMINE	NO	YES
0.340	A	0.36	LIGNOSUL	NO	YES
0.417	A	0.36	LIGNOSUL	NO	YES
0.530	A	0.42	LIGNOSUL	YES	YES
0.588	A	0.42	LIGNOSUL	YES	YES
0.351	A	0.32	LIGNOSUL	YES	YES
0.356	A	0.40	LIGNOSUL	NO	YES
0.481	A	0.40	LIGNOSUL	NO	YES
0.399	B	0.36	MELAMINE	NO	YES
0.360	B	0.36	MELAMINE	NO	YES
0.378	B	0.36	MELAMINE	NO	YES
0.326	B	0.36	LIGNOSUL	NO	YES
0.365	B	0.36	LIGNOSUL	NO	YES
0.473	B	0.42	LIGNOSUL	YES	YES
0.466	B	0.42	LIGNOSUL	YES	YES
0.410	B	0.32	LIGNOSUL	YES	YES
0.397	B	0.32	LIGNOSUL	YES	YES
0.378	B	0.40	LIGNOSUL	NO	YES
0.343	B	0.40	LIGNOSUL	NO	YES
0.380	C	0.36	MELAMINE	NO	YES
0.400	C	0.36	MELAMINE	NO	YES
0.344	C	0.36	MELAMINE	NO	YES
0.410	C	0.36	LIGNOSUL	NO	YES
0.380	C	0.36	LIGNOSUL	NO	YES
0.484	C	0.42	LIGNOSUL	YES	YES
0.496	C	0.42	LIGNOSUL	YES	YES
0.329	C	0.40	LIGNOSUL	NO	YES

(Continued)

(Sheet 1 of 3)

Table 32 (Continued)

Abrasion- Erosion cc/cu cm	AWA	W/C	HRWR	Fly Ash	Silica Fume
0.374	C	0.40	LIGNOSUL	NO	YES
0.432	D	0.36	MELAMINE	NO	YES
0.440	D	0.36	MELAMINE	NO	YES
0.451	D	0.36	MELAMINE	NO	YES
0.381	D	0.36	LIGNOSUL	NO	YES
0.413	D	0.36	LIGNOSUL	NO	YES
0.455	D	0.42	LIGNOSUL	YES	YES
0.428	D	0.42	LIGNOSUL	YES	YES
0.384	D	0.40	LIGNOSUL	NO	YES
0.378	D	0.40	LIGNOSUL	NO	YES
0.371	E	0.36	MELAMINE	NO	YES
0.385	E	0.36	MELAMINE	NO	YES
0.303	E	0.36	LIGNOSUL	NO	YES
0.393	E	0.36	LIGNOSUL	NO	YES
0.452	E	0.42	LIGNOSUL	YES	YES
0.433	E	0.42	LIGNOSUL	YES	YES
0.325	E	0.40	LIGNOSUL	NO	YES
0.360	E	0.40	LIGNOSUL	NO	YES
0.349	NONE	0.36	NAPHTHALENE	NO	YES
0.341	NONE	0.36	NAPHTHALENE	NO	YES
0.330	NONE	0.36	NAPHTHALENE	NO	YES
0.356	NONE	0.36	NAPHTHALENE	NO	YES
0.333	NONE	0.36	NAPHTHALENE	NO	YES
0.365	NONE	0.36	NAPHTHALENE	NO	YES
0.288	NONE	0.36	NAPHTHALENE	NO	YES
0.332	NONE	0.36	NAPHTHALENE	NO	YES
0.319	NONE	0.36	NAPHTHALENE	NO	YES
0.296	C	0.36	NAPHTHALENE	NO	YES
0.363	C	0.36	NAPHTHALENE	NO	YES
0.422	D	0.36	NAPHTHALENE	NO	YES
0.314	D	0.36	NAPHTHALENE	NO	YES
0.396	NONE	0.40	NAPHTHALENE	NO	YES
0.385	NONE	0.40	NAPHTHALENE	NO	YES
0.355	NONE	0.40	NAPHTHALENE	NO	YES
0.366	NONE	0.40	NAPHTHALENE	NO	YES
0.389	NONE	0.40	NAPHTHALENE	NO	YES
0.307	NONE	0.40	NAPHTHALENE	NO	YES
0.370	NONE	0.40	NAPHTHALENE	NO	YES
0.391	NONE	0.40	NAPHTHALENE	NO	YES
0.328	NONE	0.40	NAPHTHALENE	NO	YES
0.423	NONE	0.32	NAPHTHALENE	YES	YES
0.402	NONE	0.32	NAPHTHALENE	YES	YES
0.366	NONE	0.32	NAPHTHALENE	YES	YES
0.370	NONE	0.32	NAPHTHALENE	YES	YES
0.367	NONE	0.32	NAPHTHALENE	YES	YES

(Continued)

(Sheet 2 of 3)

Table 32 (Concluded)

<u>Abrasion- Erosion cc/cu cm</u>	<u>AWA</u>	<u>W/C</u>	<u>HRWR</u>	<u>Fly Ash</u>	<u>Silica Fume</u>
0.367	NONE	0.32	NAPHTHALENE	YES	YES
0.429	NONE	0.32	NAPHTHALENE	YES	YES
0.406	NONE	0.32	NAPHTHALENE	YES	YES
0.423	NONE	0.32	NAPHTHALENE	YES	YES
0.370	NONE	0.32	NAPHTHALENE	YES	YES

(Sheet 3 of 3)

Table 33
Results of Duncan's Multiple Range Test for the Effects of
AWA on Abrasion-Erosion Characteristics of Concrete

<u>Grouping</u>	<u>Means</u>	<u>Number of Samples</u>	<u>AWA</u>
A	0.42420	10	A
A B	0.40891	11	D
B C	0.39045	11	B
B C	0.38691	11	C
B C	0.37775	8	E
C	0.37270	44	NONE

Groupings with the same letter are not significantly different.

Table 34
Results of Duncan's Multiple Range Test for the Effects of
W/C on Abrasion-Erosion Characteristics of Concrete

<u>Grouping</u>	<u>Means</u>	<u>Number of Samples</u>	<u>W/C</u>
A	0.45471	14	0.42
A	0.45300	2	0.38
B	0.39085	13	0.32
B	0.37040	42	0.36
B	0.37035	23	0.40
C	0.28400	1	0.45

Groupings with the same letter are not significantly different.

Table 35
Results of Duncan's Multiple Range Test for the Effects of
HRWR on Abrasion-Erosion Characteristics of Concrete

<u>Grouping</u>	<u>Means</u>	<u>Number of Samples</u>	<u>HRWR</u>
A	0.40495	39	LIGNOSULFONATE
A B	0.39241	17	MELAMINE
B C	0.37571	7	HCA
C	0.36306	32	NAPHTHALENE

Groupings with the same letter are not significantly different.

Table 36
Results of Duncan's Multiple Range Test for the Effects of
Fly Ash on Abrasion-Erosion Characteristics of Concrete

<u>Grouping</u>	<u>Means</u>	<u>Number of Samples</u>	<u>Fly Ash</u>
A	0.430379	29	YES
B	0.367136	66	NO

Table 37
Results of Duncan's Multiple Range Test for the Effects of Silica
Fume on Abrasion-Erosion Characteristics of Concrete

<u>Grouping</u>	<u>Means</u>	<u>Number of Samples</u>	<u>Silica Fume</u>
A	0.38730	88	YES
A	0.37571	7	NO

APPENDIX A:
TEST METHOD FOR DETERMINING THE RESISTANCE OF FRESH CONCRETE
TO WASHING OUT IN WATER

Scope

1. This test method covers a procedure for measuring the amount of cement paste that washes out of concrete when coming in contact with a large volume of water. The apparatus is shown in Figure A1.

Applicable Documents

2. Applicable American Society for Testing and Materials Standards are:

- C 172 Method of Sampling Freshly Mixed Concrete
- C 143 Method for Slump of Portland Cement Concrete
- C 231 Method for Air Content of Freshly Mixed Concrete by the Pressure Method

Apparatus

3. The testing apparatus required includes:

a. A cylindrical clear plastic tube of the following dimensions:

- inside diameter = 190 mm \pm 2 mm
- outside diameter = 200 mm \pm 2 mm
- height = 2,000 mm \pm 2 mm

b. A cylindrical receiving container, with cover, both made out of perforated sheet steel having a nominal thickness of 1.5 mm. The perforations have a nominal diameter of 3 mm and a nominal distance between each of 5 mm. The outside dimensions should be:

- diameter = 130 mm \pm 2 mm
- height = 120 mm \pm 2 mm

c. A rope with a length of 2-1/2 m attached to the metallic receiving container.

d. A scale allowing determination of the mass of the sample with a precision of 0.05 percent of its mass.

Sample

4. The sample of concrete shall be representative of the entire batch and shall be obtained in accordance with Method C 172. If the concrete contains coarse aggregate particles that would be retained on a 37.5-mm (1-1/2-in.) sieve, wet sieve a representative sample over a 37.5-mm (1-1/2-in.) sieve to yield somewhat more than enough to fill the receiving

container to the desired level. The wet sieving procedure is described in Method C 172.

Procedure

5. Prepare the apparatus as follows:

- a. Level the tube base.
- b. Fill the plastic cylindrical tube with water to a height of $1,700 \pm 5$ mm.

6. Measure washout as follows:

- a. Measure the mass of the metallic receiving container, with cover, on the scale.
- b. Put a sample of fresh concrete, weighing slightly in excess of 2,000 g, into the receiving container.
- c. Rod the sample 10 times with a 9.5-mm rod. Tap the side of the container 10 to 15 times. Clean the extruded concrete from the outside of the container and record the mass of the concrete as M_1 ($2,000 \pm 20$ g).
- d. Put the receiving container holding the sample along with its cover into the plexiglas tube and lower until its bottom is in contact with the level of the water.
- e. Let the receiving container fall in a free-fall in the column of water to the bottom of the tube.
- f. After waiting 15 sec, bring the receiving container up in 5 ± 1 sec.
- g. Let the receiving container drain for 2 min, tilting slightly to allow water to run off the top of the sample. Determine the mass of the concrete remaining in the receiving container and record as M_2 . The loss in mass of the concrete in the receiving container is equal to $M_1 - M_2$.
- h. The sequence is repeated three times on the same sample, determining M_2 each time.

7. Washout, or loss of mass of the sample, expressed as a percentage of the initial mass of the sample is given by the following formula:

$$D = \frac{M_1 - M_2}{M_1} \times 100$$

where:

D = Washout, %

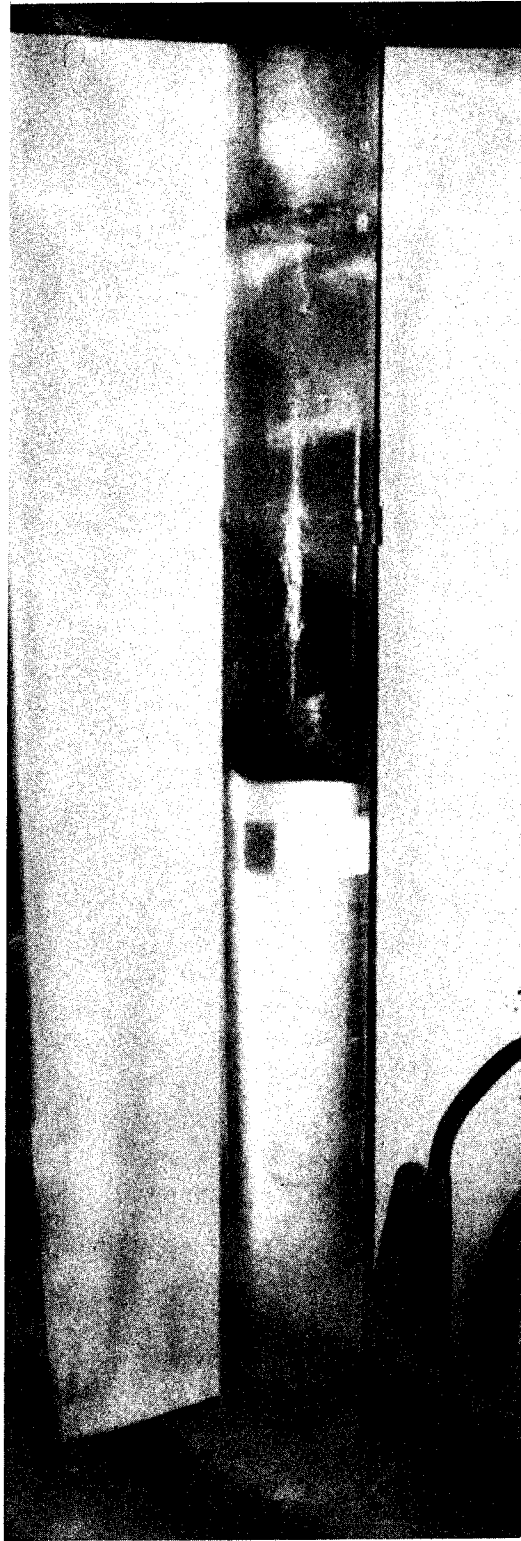


Figure A1. Washout apparatus

APPENDIX B:
TEST METHOD FOR TWO-POINT WORKABILITY (Wykeham Farrance)

Scope

1. This test method covers a procedure for measuring rheological properties of concrete by measuring the amount of torque required to turn an impeller in the concrete at varying speeds. The assembled apparatus is shown in Figure B1.

Applicable Documents

2. Applicable American Society for Testing and Materials Standards are:
- C 172 Method of Sampling Freshly Mixed Concrete
 - C 143 Method for Slump of Portland Cement Concrete
 - C 231 Method for Air Content of Freshly Mixed Concrete by the Pressure Method

Apparatus

Two-point apparatus

3. The drive system shall have a 1/2-hp electric motor operating through an infinitely variable hydraulic transmission and a 4.75:1 worm-and-pinion right-angled reduction gear. All parts shall be mounted on a simple frame, fabricated from a steel angle section, and provided with adjustable feet for leveling and castors for ease of movement. A 0 to 1,000-psi pressure gage, suitably mounted to reduce the effects of vibration shall be connected to the gear box. A snubber shall be included in the hydraulic line to reduce oscillations. A rack-and-pinion gear shall be provided to raise and lower the concrete bowl. The system is shown in Figure B2.

Impeller

4. The impeller shall be made from flat blades fixed in a helical thread cut in the central shaft in a manner that permits concrete to fall back through the gaps. The interrupted helical screw is shown in Figure B3.

Bowl

5. The bowl shall be a metal container not readily attached by the cement paste. The bowl shall be of the dimensions shown in Figure B3.

Sample

6. The sample of concrete shall be representative of the entire batch and shall be obtained in accordance with Method C 172. If the concrete contains coarse aggregate particles that would be retained on a 37.5-mm (1-1/2-in.) sieve, wet sieve a representative sample over a 37.5-mm (1-1/2-in.) sieve to yield somewhat more than enough to fill the bowl to the desired level. The wet sieving procedure is described in Method C 172.

Procedure

Preparation of the apparatus

7. Prepare the apparatus for testing as follows:
 - a. Fill and bleed the hydraulic system and fill the reduction gear box.
 - b. Check that the speed control unit is correctly zeroed.
 - c. Check that brass snubber valve and the valve in the hydraulic line are set correctly.
 - d. Set speed at 2 rps with impeller rotating anticlockwise and allow apparatus to warm up for about 30 min.

Measure workability

8. Measure workability as follows:
 - a. Fit helical impeller to shaft and fit 254-mm bowl.
 - b. Raise bowl to working position, this is when the center of the impeller shaft is 60 mm above the bottom of the bowl.
 - c. Set speed at 0.50 rps with the impeller rotating anticlockwise.
 - d. Fill bowl, gradually, with concrete to 75 mm from the rim, at the same time keeping an eye on the rise in pressure so the machine is not overloaded.
 - e. Increase speed setting and allow time for pressure to stabilize.
 - f. Read speed on tachometer.
 - g. Read pressure gage; large oscillations due to trapping of the aggregates should be ignored and an average position of the needle for the small oscillations should be recorded.
 - h. The speed and pressure are then recorded at seven different speeds*.

* For practical site or plant work it is normally sufficient to take readings at four speeds only. (The experimental error will be somewhat greater.)

1. Record the idling pressures with the bowl removed at the speeds used in paragraph 8h.

Calculation of results

9. Calculation of results is best shown by means of the following worked example. The test was carried out on a mix of aggregate-cement ratio 4-1/2:1, 40-percent fines, slump 100 mm. The calibration coefficient for the apparatus was 0.0215.

The experimental results are tabulated as follows:

Pressure Gage Readings

<u>Speed Setting</u>	<u>Speed (rpm)</u>	<u>Total Pressure</u>	<u>Idling Pressure</u>	<u>Net Pressure</u>	<u>Impeller Speed (rps)</u>	<u>Torque (Nm)</u>	<u>Comments</u>
4	380	410	150	260	1.33	5.58	
3-1/2	347	386	145	241	1.22	5.17	
3	300	363	140	223	1.05	4.79	
2-1/2	250	335	133	200	0.88	4.29	
2	200	312	130	182	0.70	3.91	
1-1/2	147	290	125	165	0.52	3.54	
1	95	265	120	143	0.33	3.07	

For the above table of figures the CORRELATION COEFFICIENT (r) = 0.998
SLOPE (h) = 2.45
INTERCEPT (g) = 2.23

The calculation can be carried out easily with any inexpensive calculator capable of regression analysis.

Calculation of Errors

Error on h

10. Select line on graph in Figure B4 corresponding to number of experimental points. In this case, $n = 7$. Knowing correlation coefficient (in this case, 0.998), read off error on h . In this case, it is approximately 5 percent.

Error on g

11. Multiply error on h by $0.95 \frac{h}{g}$

In this case

$$\text{error on g} = 0.95 \times \frac{2.45}{2.23} \times 5 = 5\%$$

Results

12. The report shall include the following data as are pertinent to the variables studied in the tests:

a. Properties of concrete mixture:

- (1) Type and proportions of cement, fine aggregate, coarse aggregate water-cement ratio, and sand-aggregate ratio.
- (2) Kind and proportions of any addition or admixture used.
- (3) Air content of fresh concrete.
- (4) Slump of fresh concrete.

b. Two-point workability:

- (1) Pressure measurements at a minimum of two speed settings (note 2) with the impeller inserted into the concrete.
- (2) Pressure measurements at the same speed settings as used with the impeller not inserted into the concrete.
- (3) Calibration coefficient (supplied by the manufacturer for each machine).
- (4) Torque value as calculated from the pressure measurements.
- (5) Plotted values of torque versus speed, with torque being on the x-axis and speed being on the y-axis.
- (6) The correlation coefficient of the linear regression line through the torque versus speed points.
- (7) The x-intercept (g) representing the yield value.
- (8) The inverse of the slope of the line (h).

Additional points will better define the line. Experiments have shown probable error in plotting the line reduces significantly when the number of measurements is increased, up to approximately seven.

Testing of Low-Workability Concretes

13. To test low-workability concretes, it is necessary to use an impeller of a different shape and to cause that impeller to rotate in planetary motion. The equipment to make this modification is available as an optional extra. In this modified form, the apparatus has been used successfully in the laboratory and onsite for concretes with a slump as low as 25 mm. However, difficulties are sometimes experienced, and it is recommended that for any particular application preliminary trials should be carried out. The basic test procedure and the calculation of results are the same as for the standard apparatus, so only the modification and differences will be listed.

- a. Remove the 4.75 reduction gear and replace with the 20:1 reduction gear and fit the planetary motion unit to the impeller shaft.
- b. Fit the H-shaped impeller to the shaft on the planetary unit.
- c. Fit the 356-mm bowl instead of the 254-mm bowl.
- d. The working clearance is 90 mm from the center of the shaft to the bowl.
- e. Fill the bowl to 140 mm from the rim (45 kg of concrete, approximately).
- f. Use as many as seven different speed settings.

14. Because of the use of planetary motion, the oscillations of pressure readings are somewhat worse, and correspondingly the correlation coefficients obtained are somewhat lower than when uniaxial rotation is used. Consequently, the experimental errors on g and h are larger. By suitable calibration with materials of known rheological properties, it is possible to interrelate the results from the two forms of machine. As a rough guide, it may be said that the values of g obtained from the two forms of apparatus are about the same but the value of h obtained with the H-shaped impeller in planetary motion is about 30 percent higher than that obtained with the helical impeller in uniaxial motion.

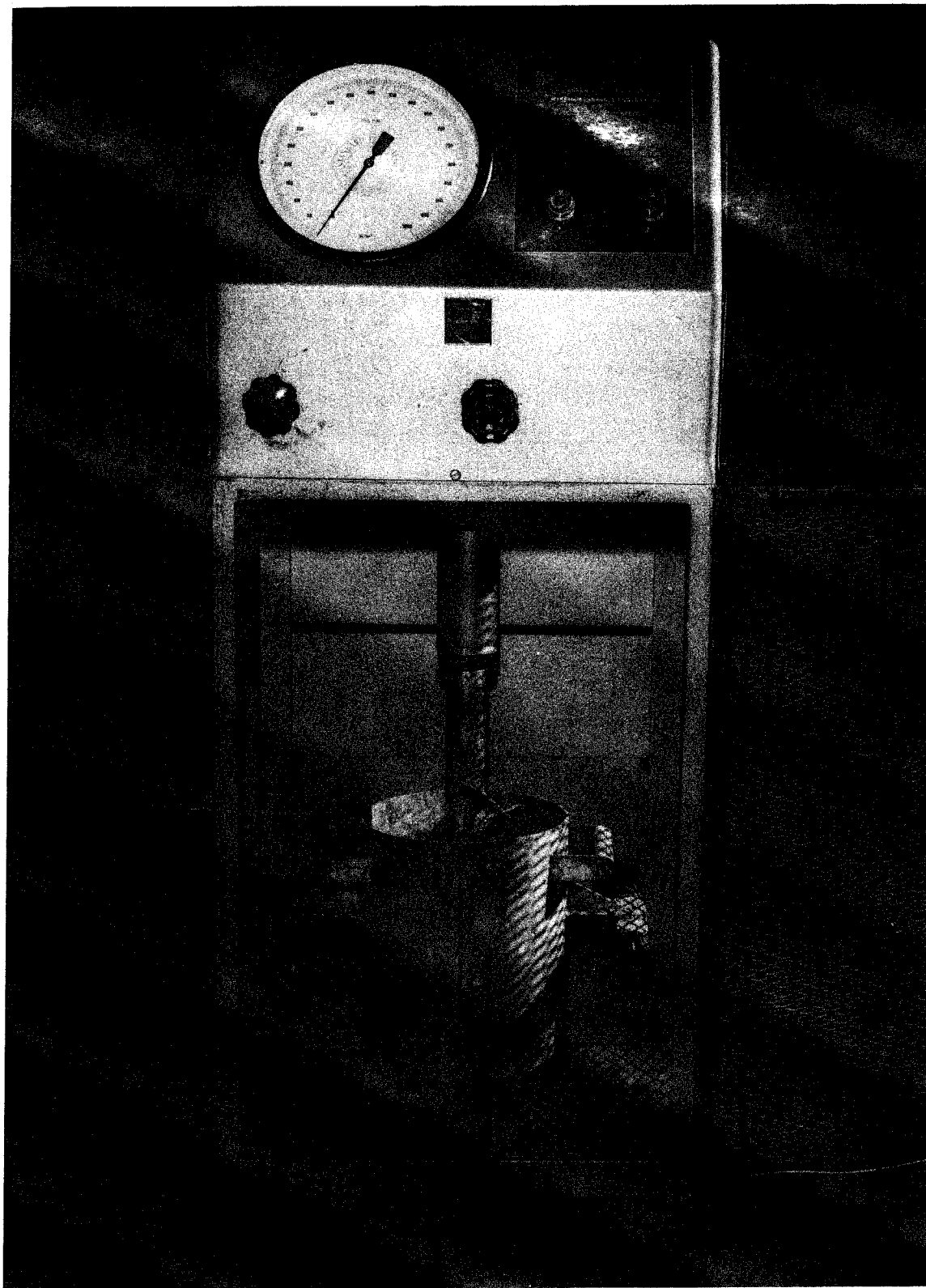


Figure B1. Assembled two-point apparatus

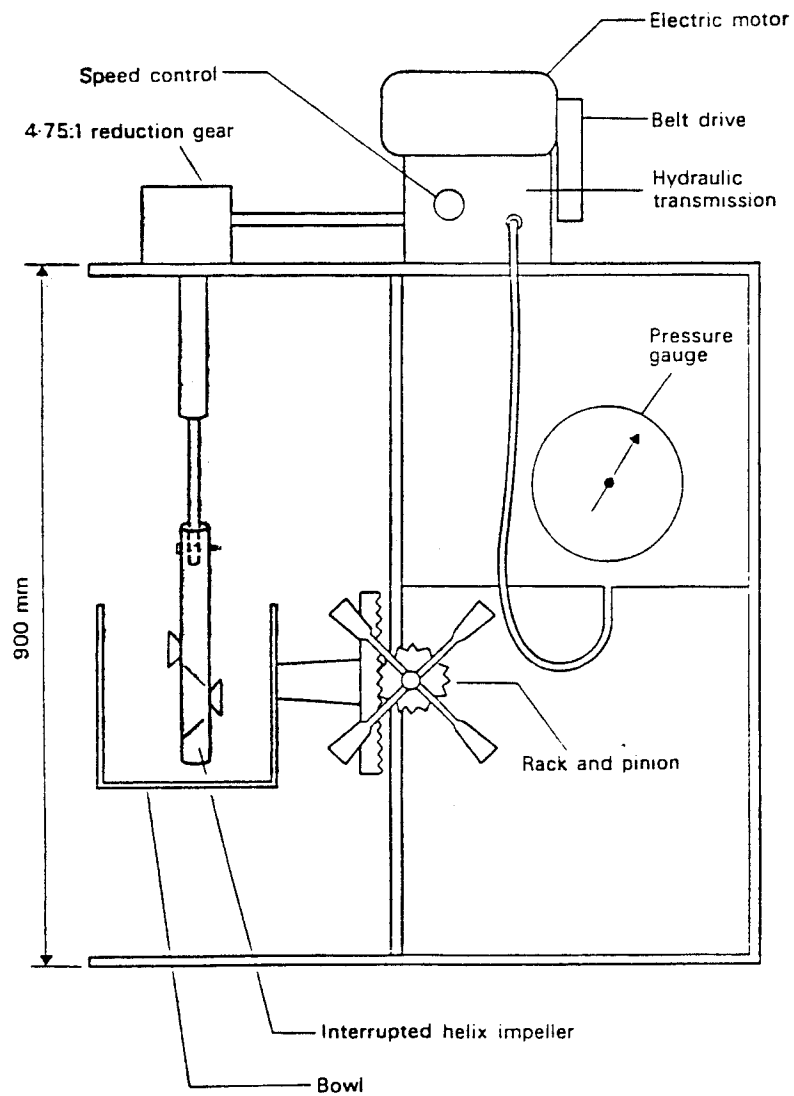


Figure B2. Two-point apparatus (Tattersall and Banfill 1983)

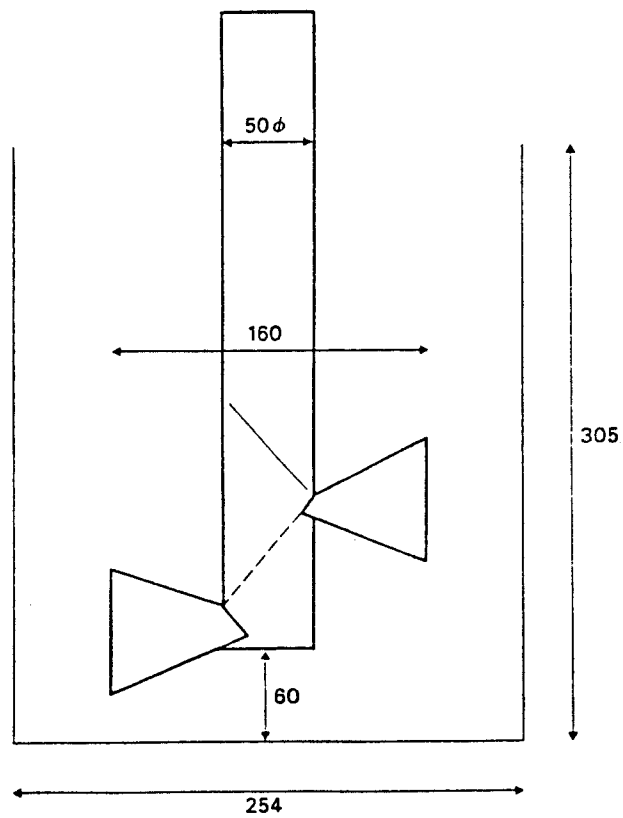


Figure B3. Helical screw and bowl
(dimensions are in mm) (Tattersall
and Banfill 1983)

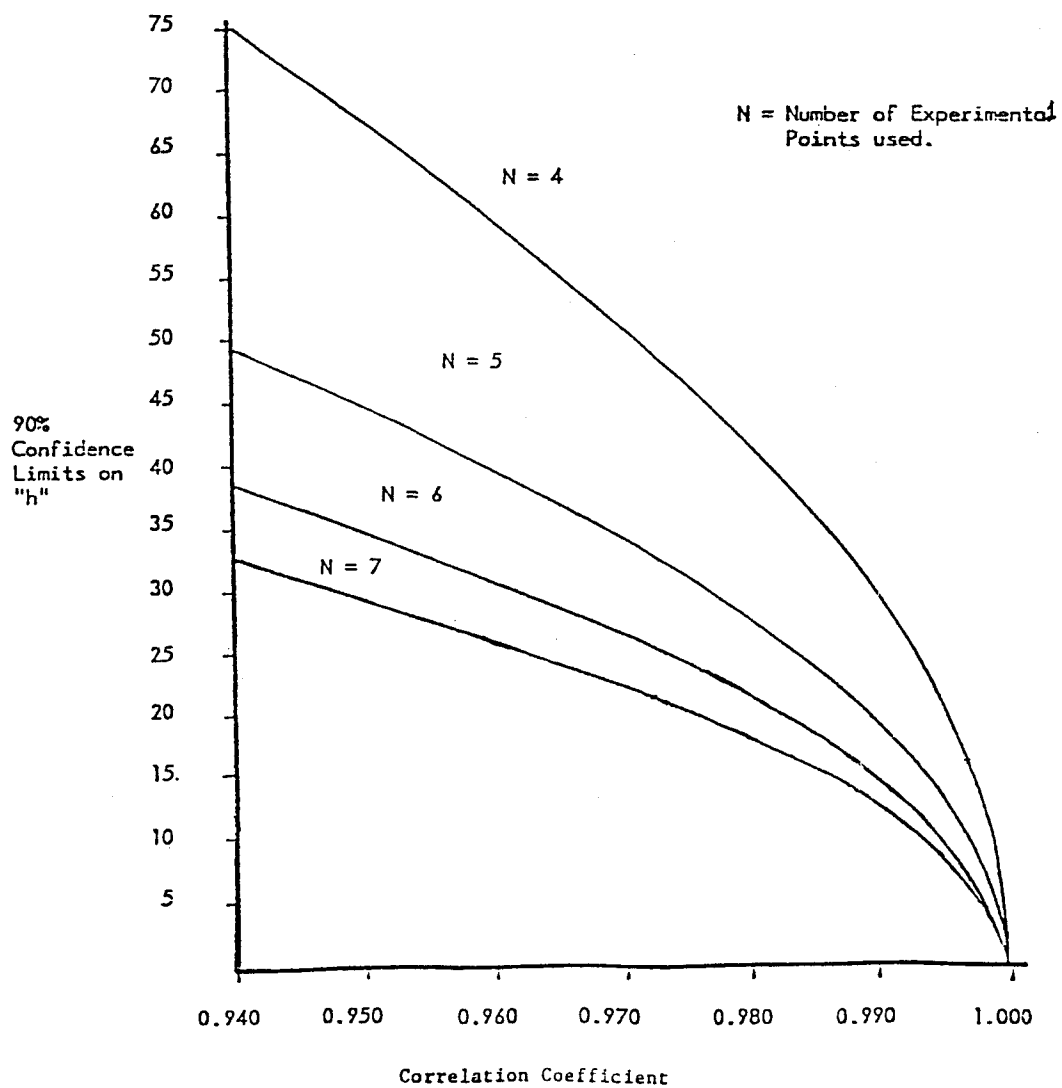


Figure B4. Relationship between 90-percent confidence limits on "h," number of experimental points, and correlation coefficient (Wykeham Farrance)

APPENDIX C:

ANALYSIS OF THE VARIABILITY OF THE ABRASION-EROSION TEST (CRD-C 63-80,
Handbook for Concrete and Cement, US Army Engineer Waterways
Experiment Station 1949)

1. In order to determine the variability of the abrasion-erosion test, a total of 27 specimens were cast from mixtures 1CON, 2CON, and 3CON. The data were analyzed using analysis of variance to determine (1) if there was a difference in the top and bottom surfaces and (2) how many samples must be tested to allow no more than a 10 percent error at a 90 percent confidence interval. The collected data is shown in Table C1.

Difference between Top and Bottom Surfaces

2. A two-way analysis of variance using the means of each sample was used to determine if there was a difference between the top and bottom surfaces.

	1CON	2CON	3CON	Avg
Top	0.414	0.428	0.406	0.416
Bottom	0.365	0.395	0.335	0.365

Ho: μ 1CON = μ 2CON ; μ 2CON = μ 3CON ; μ 1CON = μ 3CON

Hi: μ 1CON \neq μ 2CON ; μ 2CON \neq μ 3CON ; μ 1CON \neq μ 3CON

$$F_{col} = \frac{CSS / (C - 1)}{Res / (R - 1) (C - 1)}$$

$$Res = SS - RSS - CSS$$

$$\text{Total sum of squares (SS)} = 0.0059495$$

$$\text{Row sum of squares (RSS)} = 0.0039015$$

$$\text{Column sum of squares (CSS)} = 0.0016840$$

$$\text{Number of columns (C)} = 3$$

$$\text{Number of rows (R)} = 2$$

$$F_{col} = 4.63 \quad (2,2)$$

$$F_{0.05} (2,2) = 9.00$$

3. At a 90 percent confidence interval, the F-statistic with 2 degrees of freedom in the numerator and denominator is 9.00. Since F_{col} is within this region, there is no indication of a significant difference between 1CON, 2CON, and 3CON. Therefore H_0 cannot be rejected.

Ho: μ top = μ bottom

Hi: μ top \neq μ bottom

$$F_{row} = \frac{RSS / (R - 1)}{Res / (R - 1) (C - 1)}$$

$$F_{row} = 21.44$$

$$F_{0.05} (1,2) = 8.50$$

4. At a 90 percent confidence interval, the F-statistic with 1 degree of freedom in the numerator and 2 degrees of freedom in the denominator is 8.50. Since F row falls outside this region, there is an indication of a significant difference between the top and bottom surfaces. Therefore H_0 can be rejected.

Standard Deviation for Top and Bottom Surfaces

5. A one-way analysis of variance using all data was used to determine an estimate for standard deviation for both the top and bottom surfaces. See Table C1 for the data.

Top surface

$$H_0: \sigma_1^2 = \sigma_3^2$$

$$H_1: \sigma_1^2 \neq \sigma_3^2$$

$$F = \frac{\sigma_{\max}^2}{\sigma_{\min}^2} = \frac{0.00485}{0.00200} = 2.43$$

$$F_{0.05}(8,7) = 2.75$$

6. At a 90 percent confidence interval, the F-statistic for 8 degrees of freedom in the numerator and 7 degrees of freedom in the denominator is 2.75. Since the calculated F-value falls within this region, there is no indication of a significant difference between the variances of 1CON, 2CON, and 3CON. Therefore H_0 cannot be rejected.

Calculate an estimate for standard deviation (σ)

$$H_0: \mu_{1CON} = \mu_{2CON} ; \mu_{2CON} = \mu_{3CON} ; \mu_{1CON} = \mu_{3CON}$$

$$H_1: \mu_{1CON} \neq \mu_{2CON} ; \mu_{2CON} \neq \mu_{3CON} ; \mu_{1CON} \neq \mu_{3CON}$$

$$F = \frac{TSS / (K - 1)}{ESS / (N - K)}$$

$$\text{Treatment sum of squares (TSS)} = 0.0022$$

$$\text{Error sum of squares (ESS)} = 0.0840$$

$$SS = 0.0863$$

$$\text{Number of groups of data (K)} = 3$$

$$\text{Total number of data (N)} = 26$$

$$F = 0.31 (2,23)$$

$$F_{0.05}(2,23) = 2.55$$

7. At a 90 percent confidence interval the F-statistic for 2 degrees of freedom in the numerator and 23 degrees of freedom in the denominator is 2.55. Since the calculated F-value is within this region, there is no indication of a significant difference between the data in 1CON, 2CON, and 3CON. Therefore H_0 cannot be rejected.

Number of samples

$$s^2 = \frac{ESS}{N - K}$$

$$s^2 = 0.00365$$

$$\sigma \approx s = 0.0604$$

$$\mu \approx \bar{x} = 0.416$$

$$10\% \text{ error} = 0.1\mu = 0.0416$$

$$t_{\sigma/2} = 1.708$$

$$\text{Stein's two-stage sample } N = \frac{t_{\sigma/2}^2}{E}$$

$N = 7$ samples @ a 90 percent confidence interval

Bottom surface

$$H_0: \sigma_1^2 = \sigma_3^2$$

$$H_1: \sigma_1^2 \neq \sigma_3^2$$

$$F = \frac{0.000830}{0.000453} = 1.83$$

$$F_{0.05}(8,8) = 2.59$$

8. At a 90 percent confidence interval the F-statistic for 8 degrees of freedom in the numerator and denominator is 2.59. Since the calculated F-value falls within this region, there is no indication of a significant difference between the variances of 1CON, 2CON, and 3CON. Therefore, H_0 cannot be rejected.

Calculate an estimate for (σ)

$$H_0: \mu_{1CON} = \mu_{2CON} ; \mu_{2CON} = \mu_{3CON} ; \mu_{1CON} = \mu_{3CON}$$

$$H_1: \mu_{1CON} \neq \mu_{2CON} ; \mu_{2CON} \neq \mu_{3CON} ; \mu_{1CON} \neq \mu_{3CON}$$

$$TSS = 0.0164$$

$$ESS = 0.173$$

SS = 0.0337
K = 3
N = 27
F = 11.35 (2,24)
F 0.05 (2,24) = 2.54

9. At a 90 percent confidence interval the F-statistic for 2 degrees of freedom in the numerator and 24 degrees of freedom in the denominator is 2.54. Since the calculated F-value is outside this region, there is an indication of a significant difference between the data in 1CON, 2CON, and 3CON. Therefore H_0 can be rejected.

Number of samples

$$s^2 = 0.00721$$

$$\sigma \approx s = 0.0268$$

Since $\mu 1CON \neq \mu 2CON \neq \mu 3CON$, the most critical value, $\mu 3CON$, is chosen to calculate the number of samples which need to be tested.

$$10\% \text{ error} = 0.1 \mu 3CON = 0.0335$$

$$t_{\sigma/2} = 1.706$$

N = 2 samples @ a 90 percent confidence interval

Conclusion

10. There is more variability in the testing of the top surface and therefore requires more samples to get an equally precise value for the volume loss during the test. The data indicate that four times as much testing would be required if the top were tested to produce results of equivalent precision. Since it was regarded as more important to evaluate the maximum number of concretes using the available resources, tests will be made using bottoms only in spite of the fact that top-to-bottom differences may vary from concrete to concrete. Only the top as cast of any concrete will initially be exposed to abrasion. Since the aggregate is chert, the layer of mortar at the top will abrade more rapidly than the concrete with coarse aggregate, hence the thickness of the mortar layer will markedly affect abrasion loss in the early stages. However, once abrasion removes the mortar layer, subsequent abrasion-resistance behavior of the concrete would be expected to be proportional to the results of tests on the specimen bottom.

Table C1
Abrasion Loss at 72-Hour Testing Time

CYL.	CUMULATIVE LOSS, cc/sq cm					
	TOP			BOTTOM		
	1CON	2CON	3CON	1CON	2CON	3CON
1	0.338	0.422	0.448	0.396	0.423	0.349
2	0.270	0.392	0.304	0.385	0.402	0.341
3	0.418	0.417	0.400	0.355	0.366	0.330
4	0.456	0.452	0.396	0.366	0.370	0.356
5	0.439	0.441	0.411	0.389	0.367	0.333
6	0.392	0.345	0.459	0.307	0.429	0.365
7	0.433	0.544	0.436	0.370	0.406	0.288
8	0.526	0.392	0.396	0.391	0.423	0.332
9	0.451	0.451	*	0.328	0.370	0.319
\bar{x}	0.414	0.428	0.406	0.365	0.395	0.335
s^2	0.00485	0.00271	0.00200	0.00083	0.00064	0.00045

* Bad test

